PB81-248155

Proceedings of the Conference on Wood Combustion Environmental Assessment Held at New Orleans in February 1981

Research Triangle Inst.
Research Triangle Park, NC

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

1981

U.S. Department of Commerce
National Technical Information Service
NTIS

PB81-248155

EPA-600/9-81-029

Proceedings: Conference on Wood Combustion Environmental Assessment (New Orleans, February 1981)

Franklin A. Ayer, Compiler

Research Triangle Institute
P. O. Box 12194
Research Triangle Park, NC 27709

Contract No. 68-02-3170
Task No. 31
Program Element No. C9KN1C

EPA Project Officer: Michael C. Osborne

Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

NOTICE

THIS DOCUMENT HAS BEEN REPRODUCED FROM THE BEST COPY FURNISHED US BY THE SPONSORING AGENCY. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE.

IERL-RTP-1235

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO. PB81 248155
4. TITLE AND SUBTITLE Proceedings: Conference on Wood Combustion Environmental Assessment (New Orleans, February 1981)		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Franklin A. Ayer (Compiler)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Research Triangle Institute P.O. Box 12194 Research Triangle Park, North Carolina 27709		10. PROGRAM ELEMENT NO. C9KN1C 11. CONTRACT/GRANT NO. 68-02-3170, Task 31
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Proceedings; 10/80-6/81 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Michael C. Osborne, Mail Drop 65, 919/541-4113.

16. ABSTRACT

These proceedings document presentations at the conference. The objective of the conference was to disseminate recent research and development findings on the subject of residential wood combustion. The conference sessions dealt with: (1) an overview of environmental assessment activities, (2) specific emissions and heating efficiency assessments, (3) emissions control techniques, (4) highlights of the first three sessions, and (5) residential wood combustion issues and their resolution. In summary, the previously reported high concentrations of polycyclic organic matter (POM) in residential wood stove emissions were verified by several papers. One paper even reported high POM concentrations in the indoor environment of homes with wood stoves. High ambient values were not attributed to residential wood combustion, but many of the ambient impact studies were just beginning. Emission control techniques which were considered for controlling organic emissions included secondary combustion and the introduction of a combustion catalyst. These two control techniques were already being marketed; however, their reliability and structural stability were questioned by several researchers. Future regulation of wood stove emissions was considered unlikely due to problems relating to enforcing a residential emission standard.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Heating	Pollution Control	13B	13H
Wood	Polycyclic Compounds	Stationary Sources	11L	07C
Combustion	Organic Compounds	Wood Stoves	21B	
Stoves	Catalysts	Environmental Assessment	13A	07D
Assessments			14B	
Residential Buildings		Heating Efficiency	13M	

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 330
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

PREFACE

These proceedings for the "Wood Combustion Environmental Assessment Conference" constitute the final report submitted to the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency (IERL-EPA), Research Triangle Park, NC. The conference was conducted, in cooperation with the Wood Heating Alliance (formerly the Wood Energy Institute), at the 1981 International Trade Show and Wood Heating Seminar, held at the Superdome in New Orleans, LA, on February 21-24, 1981.

The conference was convened to provide participants an opportunity to exchange and disseminate new information on wood combustion. The conference General Chairman opened the program by stating the conference objectives. Session 1 was an Overview of Wood Combustion Environmental Assessment; Session 2 covered Assessments of Residential Wood Heating Efficiency and Emissions; Session 3 covered Emissions Control Techniques for Wood Burning Appliances; Session 4 covered Assessment and Control--Highlights from Earlier Sessions; and Session 5 was composed of a panel of experts who discussed Issues Related to the Residential Combustion of Wood and How They May Be Resolved.

Mr. Michael C. Osborne, Environmental Engineer, Chemical Process Branch, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, was Project Officer and General Chairman for the conference.

Mr. Franklin A. Ayer, Manager, Technology and Resource Management Department, Center for Technology Applications, Research Triangle Institute, Research Triangle Park, NC, was conference coordinator and compiler of the proceedings.

TABLE OF CONTENTS

Page

Statement of Conference Objectives. 1
Michael C. Osborne, General Chairman

Session 1: OVERVIEW OF WOOD COMBUSTION ENVIRONMENTAL ASSESSMENT. 3
Henry Anderson, Chairman

Residential Wood Program Overview - Department of Energy. 4
Henry Anderson

Results of the DOE Think Shop On Residential Wood Combustion 17
Charles Bendersky (Presented by Henry Anderson)

Overview of Emissions from Wood Combustion. 39
Kenneth J. Lim* and H. I. Lips

Ambient Air Assessment in a Rural New England Village Where Wood is the Dominant Fuel 55
James F. Hornig*, Roger H. Soderberg,
Deborah Larsen, and Carlo Parravano

An Integrated Environmental Assessment of Biomass Energy Development in the Tennessee Valley 69
Paul F. Schwengels*, Charles Bohac,
and Kit Krickenberger

Session 2: ASSESSMENTS OF RESIDENTIAL WOOD HEATING EFFICIENCY AND EMISSIONS. 85
Jerome P. Harper, Chairman

Residential Wood Heating Efficiency and Emissions - An Overview. 86
Jerome P. Harper

Wood Combustion Emissions at Elevated Altitudes 91
James A. Peters, Thomas W. Hughes*, and D. G. DeAngelis

Residential Indoor Air Quality and Wood Combustion. 99
Demetrios J. Moschandreas, Joseph Zabransky, Jr.*
and Harry E. Rector

Performance of Domestic Wood-Fired Appliances 109
A. C. S. Hayden* and R. W. Braaten

*Denotes speaker

Page

An Assessment of the Efficiency and Emissions of Ten Wood Fired Furnaces 120
Robert J. Brandon

Results of Laboratory Tests on Wood-Stove Emissions and Efficiency. 142
Bill R. Hubble* and J. B. L. Harkness

Session 3: EMISSIONS CONTROL TECHNIQUES FOR WOOD BURNING APPLIANCES. 161
Wade H. Ponder, Chairman

Catalytic Combustion in Residential Wood Stoves 162
Robert V. VanDewoestine*, Frank Zimar, and Roger A. Allaire

Catalytically Assisted Combustion in Residential Wood-Fueled Heating Appliances. 175
Jay W. Shelton

Measurements of Chemical Changes Due to Catalysis of Woodstove Effluent 202
Dennis R. Jaasma

A Simplified Technique for Measuring Condensable Particulate Emissions from Woodstoves 212
Stockton G. Barnett* and Damian Shea

Control of Emissions from Residential Wood Burning by Combustion Modification. 222
John M. Allen

Session 4: ENVIRONMENTAL ASSESSMENT AND CONTROL - HIGHLIGHTS FROM EARLIER SESSIONS 247
Robert E. Hall, Chairman

Highlights from Session 1 - Overview of Wood Combustion Environmental Assessment. 248
Henry Anderson

Highlights from Session 2 - Assessments of Residential Wood Heating Efficiency and Emissions 254
Jerome P. Harper

Session 5: PANEL - ISSUES RELATED TO THE RESIDENTIAL COMBUSTION OF WOOD AND HOW THEY MAY BE RESOLVED 258
Michael C. Osborne, Chairman

*Denotes speaker

Page

Combustion of Wood/Environmental Restrictions in Sweden 259
Jan Nilsson

Institutional and Regulatory Approaches to Control Residential Wood Burning Emissions. 265
W. T. Greene* and Barbara J. Tombleson

Residential Wood Combustion Issues for the Tennessee Valley. 285
Charles E. Bohac*, Joseph R. Duncan, and Larry E. Beeman

Wood Energy - The North Carolina Effort 297
Phyllis Brooks Wainwright

Preliminary Analysis of the Ambient Impacts of Residential Woodburning in Waterbury, Vermont. 303
Cedric R. Sanborn*, Richard L. Poirot, Gregory A. Heil, and Michael A. Blanchet

Pollution and Fireplaces in California. 314
Peter H. Kosel

*Denotes speaker

STATEMENT OF CONFERENCE OBJECTIVES

Michael C. Osborne
U.S. Environmental Protection Agency
Industrial Environmental Research Laboratory
Research Triangle Park, NC

Wood combustion has been an important source of energy since the dawn of civilization. In the United States wood was replaced as a major source of energy in the 1880's because of the lower cost, easier distribution and handling, and greater availability of coal and oil, as well as the increased demand for wood in construction and manufacture of paper and pulp products. Since 1973, however, increasing costs of other fuels have been responsible for reviving the use of wood for residential heating.

In the United States residential wood combustion already provides the heat equivalent of 140,000 barrels (22,260 cubic meters) of oil daily and the use of wood as a residential fuel continues to expand. With this expansion has come a growing concern over the potential environmental impact of wood combustion.

EPA's Industrial Environmental Research Laboratory in Research Triangle Park, North Carolina, is conducting studies aimed at better understanding the types and amounts of industrial and residential wood combustion emissions, determining the impact of wood burning on atmospheric air quality as compared to other energy sources, and learning how this pollution can be minimized by changing conventional wood burning methods.

This conference is concerned with those same three objectives: air quality impacts, source emission assessments, and control technology developments. By 1:00 p.m. on Tuesday, each of us should be well on our way to answering these three questions:

- What are the relative contributions to prevailing ambient levels of the various pollutants emitted during residential combustion of wood?
- What are the composition and rate of emissions as a function of combustor design; type, seasoning, and form of wood fuel; and combustor operating conditions?
- What control techniques appear promising?

TYPING GUIDE SHEET
BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

The conference will, obviously, not answer all of our concerns or questions, but we should be better prepared as a result of this conference to go back to our offices and laboratories and begin searching out the remaining answers with renewed enthusiasm and confidence.

6-1/2"
9-1/8"
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Session 1: OVERVIEW OF WOOD COMBUSTION ENVIRONMENTAL ASSESSMENT

Chairman: Henry Anderson
Department of Energy
Washington, DC

RESIDENTIAL WOOD PROGRAM OVERVIEW
DEPARTMENT OF ENERGY

Henry Anderson
Program Manager,
Technology and Consumer Products Branch

ABSTRACT

A major mission of the Office of Buildings and Community Systems (OBCS) is to promote the development and adoption of new energy-efficient technologies. With OBCS, the Technology and Consumer Products Branch (TCP) has the primary responsibility for developing and commercializing new space conditioning technologies for use in residential and commercial buildings. The TCP mission covers technical research, product development, and demonstration activities jointly funded with industry, educational institutions, utilities, and other federal and state agencies.

A major activity within TCP is the Heating and Cooling Program, which, for several years, has been addressing oil and gas furnaces and boilers, central air conditioning, and heat pump systems. Recently, the TCP Branch expanded its heating and cooling program responsibilities to include residential and commercial wood burning equipment such as wood stoves, fireplace inserts, furnaces, boilers, and related items.

Funding for the TCP residential wood program is provided by the Biomass Energy Systems Division, Office of Solar Applications under the Assistant Secretary for Conservation and Solar Energy.

INTRODUCTION

A major mission of the Office of Buildings and Community Systems (OBCS) is to promote the development and adoption of new energy-efficent technologies. With OBCS, the Technology and Consumer Products Branch (TCP) has the primary responsibility for developing and commercializing new space conditioning technologies for use in residential and commercial buildings. The TCP mission covers technical research, product development, and demonstration activities jointly funded with industry, educational institutions, utilities, and other federal and state agencies.

A major activity within TCP is the Heating and Cooling Program, which, for several years, has been adddressing oil and gas furnaces and boilers, central air conditioning, and heat pump systems. Recently, the TCP Branch expanded its heating and cooling program responsibilities to include residential and commercial wood burning equipment such as wood stoves, fireplace inserts, furnaces, boilers, and related items. In addition, coal has been included in TCP's programs because coal burning equipment is very similar to wood burning equipment and because the coal resource in the United States is very large and shows promise of expanding applications in the residential sector.

WOOD UTILIZATION OVERVIEW

One of the fastest growing and most popular conservation technologies in the United States is also one of the oldest. Wood and Coal stoves and fireplaces, although in use for more than 200 years, have since 1973 experienced a surge in popularity. The reason for increased interest is that this equipment has become recognized as an effective and available alternative source of space heating for residences and, to a limited extent, commercial buildings. Among the many factors enhancing the attractiveness of wood burning have been:

- Rapidly rising oil, gas, and electric prices
- Fuel supply interruptions
- The nation's large and widespread timber resources
- Development of more efficient, functional, and attractive types of residential wood and coal burning equipment
- Publicity and endorsement by Congress and the President.

As a result of these factors, the market for wood-burning stoves, inserts, and central equipment has risen dramatically, from 200,000 units per year before 1973 to approximately 1.5 million units in 1979. Various surveys now indicate that wood-burning equipment has penetrated 18 million U.S. households.

Despite the high interest in wood and coal burning and the resultant strong market demand, a number of problems are starting to emerge that may limit future market growth or may even cause present users to stop using their equipment. Among these potential problems are:

- Concern by code officials, fire marshals, insurance companies, and others about the increase in home fires attributable to solid fuel heating equipment

- Potential health problems due to the high particulate emissions, especially from air tight stoves

- Consumers buying and using inefficient equipment, resulting in uneconomical operation and fuel waste

- Rapid rise in demand for solid fuels, especially wood, causing spot shortages.

PROGRAM OBJECTIVES

In response to considerable industry, congressional, and public concern, DOE has established a research and commercialization program for wood and coal energy use in residential and commercial buildings. The specific objectives of the program are too:

- Develop technology to improve the efficiency, safety, reliability, and emissions control for wood and coal combustion equipment; and to ensure that these technologies are appropriate for wide-spread usage in the residential and commercial sectors

- Help ensure the development and availability of wood and coal burning equipment appropriate to most building applications

- Ensure that consumers, regulatory agencies, utilities, and manufacturers have adequate information and technical data on the safe and effective use of wood and coal
- Help coordinate related federal, state, and local programs in resource development, emissions control, improved safety, code and regulations development, incentives anaylsis, research, and consumer education.

One of the basic premises is that accelerated commercialization of present residential wood/coal burning technogies is not necessary since the market demand for this equipment is already large. Rather, what is needed is development of improved equipment and operating practices that can be adopted over the next 5 years, while the equipment sales levels are still significant.

NEED FOR PROGRAM

There are a number of important reasons why a DOE residential and commercial wood and coal energy program is needed. The first and most important is that wood and coal represent substantial domestic energy resources that can substitute for oil and gas. Wood is especially attractive since it is renewable and is available in the northern part of the country where direct uses of solar energy are less practical. Coal, although not renewable, is still a fossil fuel expected to be available for hundreds of years, which can substitute for the more limited supplies of other fossil fuels. Since wood and coal are domestically produced, they can help reduce the demand for costly imported fuels and thus improve the U.S. balance-of-payments position.

The second major reason why a DOE program is needed is that a significant portion of the equipment in use, especially in residences, may have been unsafely installed and operated, largely due to a lack of consumer awareness as to proper installation and operation procedures. DOE has an interest in resolving this concern.

The program is also needed because potential adverse environmental impacts such as local air pollution are a concern to DOE. Wood stoves, like diesel engines, may force a trade-off between energy conservation and environmental concerns--a trade-off that is a government policy decision.

The fourth reason is that since the market for wood burning equipment has grown so rapidly, a portion of the installations may not be as efficient as could be. This factor is important because moderate- or low-efficiency equipment is not economical to operate. Although market forces may eventually remedy this situation, DOE can potentially accelerate the development and use of improved equipment and operating practices.

RELATIONSHIP TO OTHER DOE PRODUCTS

Since the residential/Commercial wood and coal program is part of the Technology and Consumer Products (TCP) Branch the main thrust of the program is on the development of improved hardware, related testing procedures, and information dissemination. The primary market segment addressed by TCP is space heating systems for residential and commercial buildings. However, because the potential markets for wood and coal fuels are much greater than the sectors within the scope of TCP, a variety of other areas within DOE are also involved.

The lead responsibility within DOE for wood fuels development is the Division of Biomass Energy Systems (BES), which provides coordination among the residential/commerical, industrial, utility, and field programs.

The Office of Industrial Programs has the responsibility of addressing industrial wood energy use, such as forest liquors and wastes used by the paper and pulp industry. The Regional Solar Energy Centers will also address residential and commercial wood energy use in regions of the country with an adequate resource base. In addition, the Division of Anthracite Coal will be involved in coal supply and utilization development, along with the Office of Fossil Fuel Utilization.

In coordination with DOE program, the Tennessee Valley Authority has and will continue its own program of field demonstration and consumer education for residential wood stove use.

PROGRAM PRIORITIES

To ensure that the limited program resources are used effectively, it is essential that program activities be targeted towards the equipment, market, and issues of greatest concern. This requires prioritization of both market constraints and potential program activities.

The major TCP program activities for the residential and commercial use of wood energy in buildings concern:

- Fire safety
- Emissions
- Efficiency
- Fuel availability and price
- Market development

Fire Safety

Due to the relatively large and growing number of solid fuel-related home fires, the resolution of safety problems must be given a high, near-term priority in this program. The fire safety issue is of immediate concern because there are some 8 million stoves, fireplace inserts, and central heating units already in use, most of which have been owner-installed without complete safety guidelines or fire marshall or building code inspection. Recognizing the importance of the fire safety issue can therefore provide an immediate payoff in reducing the potential for personal injury and property damage.

Since considerable information already exists which may not be fully disseminated, a major near-term thrust of the program must include the distribution of consumer information regarding proper installation, operation, and maintenance procedures.

In order to better understand the fire safety issue and to direct future R&D approaches, analysis of solid fuel-related fire incidence rates, causes, and level of damage has also been asigned a high priority. Preliminary studies have been conducted by NBS and CPSC.

Although existing fire safety data are in large part adequate, there are a number of high priority research and development needs related to safety. The first priority involves clearances or distance requirements between stoves (as well as other heating equipment) and combustible materials. The original clearance standards were developed 20 or 30 years ago and were based on building materials then in use. With the introduction of new, less fire- or heat-resistant materials--such as polystyrene wall coverings--there may be a need to increase clearances from hot stove surfaces or to provide extra heat shielding.

Another high priority is to develop an improved understanding of chimney fires and how such fires can be contained. Similarly, research is needed into installation and operational procedures for new products such as fireplace inserts and furnace add-ons, for which future UL standards will apply.

Emissions

The potential market constraints posed by the particulate emissions from wood and coal burning equipment differ from other problem areas in that the basic underlying causes and detrimental health effects are not yet well understood. A near-term priority is therefore indentification of the constituents of wood and coal stove emissions, and the contribution of these emissions to local air quality problems. Emissions concerns involve longer-term effects than the fire safety issues.

Air quality studies should include basic combustion research and parametric analysis to determine how emissions products are formed and which equipment design variables can influence the rate of formation. It should be noted that although there has been extensive research into oil and gas combustion processes, there has been little work on small-scale wood combustion processes. Considerable coal combustion research conducted in the past may need to be updated.

As soon as baseline emissions information becomes available, it will be possible to accelerate the emissions program in three areas:

- Developing standardized equipment testing procedures
- Characterizing emissions outputs for various types of equipment
- Developing improved equipment designs and external control technologies.

The eventual output of the emissions-related R&D will be the dissemination of emissions information and the transfer of new technology developments to manufactuers. The long-term payoff of these activities will be improved air quality levels.

Efficiency

As a result of the recent advances made in solid fuel appliance R&D and by wood and coal burning equipment manufacturers, the need for efficiency-related R&D activities is somewhat lower than for safety or emissions. However, there are important needs in four areas:

- Consumer purchase and operation information
- Voluntary industry equipment efficiency labeling for stoves
- Advanced equipment systems R&D
- Testing and standards development for furnaces and boilers.

The availability of adequate efficiency-related information is very important to informal consumer decisions. An efficiency test standard and labeling program could potentially be very helpful to consumers on selecting wood burning equipment. A greater emphasis on efficiency information and on wider industry acceptance of the labeling program is warranted.

A final area appropriate to DOE activities in efficiency improvement is the continued development of advanced equipment designs, especially for boilers, furnaces, and add-on units. To date, the industry has taken a lead role in this regard, but the advanced R&D can outpaced the technical and financial capabilities of small equipment manufacturers, suggesting a active DOE role.

Fuel Availability and Price

The U.S. Forest Service has the primary Federal Responsibility for forest management, and DOE's Division of Biomass Energy Systems (BES) has the prime responsibility for the development of all biomass fuels. Similarly, DOE's Division of Anthracite and other offices are concerned principally with coal resources and production but place little or no emphasis on the end-use distribution channels for coal. As a result, DOE/TCP/BES role in fuel supply is primarily in three areas:

o Fuel distribution systems
o Availability of equipment for new fuels
o Identification of the need for new fuel types

The distribution link appears to be a very important aspect of ensuring an adequate supply of fuel, at least in urban areas. Most of the reported problems of wood fuel availability for residential and commercial heating applications have been in regions of the U.S. where there is a large timber resource. In addition, processed fuels to meet the needs of larger buildings may become available in the near future.

To address these issues, BES/TCP should identify the fuel wood supply infrastructure, distribution, channels, and end-user availability of fuel. Similarly, a somewhat more limited TCP effort should be directed toward coal supply infrastructure development.

Market development of New Equipment

It presently appears that this program area should receive a low near-term priority because the market, at least for residential equipment, has shown substantial growth due largely to rapidly rising prices for conventional fuels.

To ensure that wood and coal continue to be widely used in the future will probably require further development of automated residential wood burning equipment. If these fuels are to achieve even moderate penetration in commercial buildings, then there very likely will be a need for improved boilers, stokers, and fuel-handling equipment. TCP should have a samll but expanding program of product development and technology transfer, consistent with market interest and ongoing industry activities, to encourage and direct the equipment industry.

This area is extensively shared with BES and the regional solar energy centers. Non residential applications and market development of all fuels in general lies completely within the auspices of BES.

PROGRAM MANAGEMENT

The management of the residential and commercial wood and coal energy program will be based on several principles that have proven workable in related DOE programs. These principles are:

- Decentralized program management
- Utilization of extensive Federal and State capabilities for conducting R&D
- Utilization of established industry and other institutional channels for commercialization and information dissemination.

Management Structure

The basic programmatic direction and policymaking will be the responsibility of DOE headquarters. Within DOE the line program responsibility will be within the Technology and Consumer Products Branch of the Office of Buildings and Community Systems. Because the wood and coal program is closely related to TCP's space conditioning program, management resources will be common to both programs.

Because the management responsibility and funding coordination for all DOE wood energy commercialization activities is the Division of Biomass Energy Systems (BES), TCP's wood program will report administratively, through BES. Also reporting to BES will be the DOE industrial wood energy program, utility program, and field projects manager.

The field technical projects management for the TCP wood and coal program will be a national laboratory. The field manager will be responsible for:

- Issuing requests for proposals
- Evaluating proposals
- Executing contracts
- Performance monitoring for contracts
- Interaction with the private sector
- Formulating programmatic recommendations.

R&D Resources

There are a number of R&D resources available that will be used in this program. Many of these resources have already been extensively involved in wood energy and, in several cases, with DOE's former wood energy program. Among the major R&D resources are:

- NBS--which has already conducted wood-related fire safety and efficiency R&D under contract to DOE

- EPA--which is coordinating and partially sponsoring emissions-related research

- Manufacturer--having the resources for developing and commercializing wood and coal burning equipment

- R&D firms--can work in conjunction with equipment manufacturers in developing advanced wood and coal burning equipment

- National laboratories--Brookhaven and Lawrence Berkley have both been involved in limited residential wood and/or coal use

- Universities--Auburn, Maine, Georgia Tech, Oregon State, and many others
- USDA Forest Service--which is coordinating resources development.

Commercialization and Information Dissemination Resources

To bring about rapid technology transfer, information dissemination, code and standards adoption, and other commercialization processes, established industry and institutional channels will be used to the extend possible. Because many of the issues and problems related to coal and wood burning are within the purview of various interested audiences, and, in some cases, are already being addressed at a low level of effort, DOE will be able to commercialize new products, transfer technology, etc. capable and operating.

Among the main existing commercialization channels available are:

- U.S. Fire Administration--works closely with fire marshals nationwide
- National Fire Protection Administration--establishes and disseminates fire-related building codes
- Underwriters Laboratory--establishes testing procedures and maintains listing services
- Major building code organizations--BOCA, ICBO, SBCCI, and ABC
- Trade associations/publications--Wood Heating Alliance , Fireplace Institute, Gas Appliance Manufacturing Association, National Wood Stove and Fireplace Journal, American Forestry Institute
- Major utilities in regions with large wood or coal resources--TVA and BPA
- State and regional groups--New England Regional Commission and state energy offices.

Also available to DOE for assistance in Commercialization are several new DOE groups:

- Regional Solar Energy Centers--Boston, Atlanta, Minneapolis, and Portland OR
- Energy Extension Service.

It is anticipated that most if not all of these various organizations will plan a role and as the program develops further, these roles will be clarified.

Acknowledgement

Acknowledgement is given to Mr. David Hartman of Booz-Allen-Hamilton for his efforts in developing the preliminary and overall residential wood program plan, from which this paper was extracted.

RESULTS OF THE DOE THINK SHOP ON RESIDENTIAL WOOD COMBUSTION

CHARLES BENDERSKY
PYROS, INC.
GAITHERSBURG, MD.

DISCLAIMER

THIS REPORT WAS PREPARED BY PYROS, INC. AS A SOURCE DOCUMENT FOR DOE STUDY AND FOR USE IN PROGRAM DEVELOPMENT AND DOES NOT REFLECT FIRM ACTIONS PLANNED FOR OR BY DOE OR OTHER FEDERAL ORGANIZATIONS. CARE HAS BEEN TAKEN TO ENSURE THE CONTENTS OF THIS DOCUMENT REFLECT THE PROCEEDINGS OF THE MARCH 27-28, 1980 MEETING. HOWEVER, NEITHER PYROS, INC. NOR THE U.S. GOVERNMENT MAKE ANY CLAIMS OR GUARANTEES AS TO THE FACTUAL CONTENT OR USEFULNESS AND NEITHER CAN BE HELD RESPONSIBLE FOR ACTIONS BY OTHERS BASED ON THIS REPORT.

ABSTRACT

The Doe Office of Buildings and Community Systems, Technology and Consumers Products Branch convened a "Think Shop" to address the technology needs in the area of residential wood combustion emissions. The meeting was held at Battelle, Columbus Laboratories on March 27 - 28, 1980 and was attended by a group of program managers from DOE, EPA, TVA, and the Canadian Government, and a group of the leading researchers active in the field. The results were recommendations of needed activities to be undertaken in the areas of air quality, combustion technology, equipment development, and emissions measurements. It was recommended that to be effective these activities must be initiated immediately and be completed by FY 85. The needs of the program require the cooperation of the management and scientific expertise of DOE, EPA, and TVA, the pooling of available financial resources and the participation of a number of qualified research organizations. The report provides statements of needs, definitions of specific tasks, and estimates of the resources and manpower for accomplishment. This report was prepared by PYROS, Inc. as a source document for DOE study and for use in program development and does not reflect firm actions planned for or by DOE or other federal organizations.

INTRODUCTION AND SUMMARY

The DOE's Wood Commercialization Program has a goal of 4.4 quads per year of energy from wood combustion to be reached by the year 2000. With appropriate federal action, this goal can be met and sustained through proper forest management practices and utilization in combustion equipment suitable to the needs of the residential, industrial and utility markets. In the near term, a large part of the increased wood use necessary to meet this goal will take place in the residential sector, primarily for space heating. During the past several years, the sales of wood stoves, fireplace inserts, and other residential combustion appliances have markedly increased. Now more than 7 million homes use wood as a primary or secondary heat source. In 1978, the DOE anticipated this growth and implemented a rigorous research and development program designed to insure that safe, efficient appliances could be made available for the residential market place. This efficiency and safety oriented program has already succeeded in developing testing procedures for performance ratings, installation and operating procedures for regulatory and consensus standards organizations and design information to assist manufacturers in improving the performance efficiency of their proprietary equipment. (The testing procedures are now under review for acceptance as national standards.)

As the numbers of appliances rapidly increased, data began to indicate that the emissions from wood burning appliances could have significant deleterious effects on air quality in specific local air sheds. In a pioneer paper, Butcher and Sorenson* suggested that wood stoves may contribute particulate levels as high as 100 g/m^3; Cooper** obtained results which indicated that smoke from wood and wood burning stoves and fireplaces contained 17 priority pollutants, up to 14 carcinogens, 4 co-carcinogens, 6 cilia toxic and mucus coagulating agents. TVA and EPA conducted studies which further articulated potential problems attributable to residential wood stove emissions.

These preliminary adverse assessments were compounded by the realization that much of the residential wood combustion occurs in airsheds which are candidates for large increases in industrial wood burning and coal combustion. Since residential wood burning was rapidly penetrating the market, it became evident that a federally sponsored high priority program is required to provide solutions to protect the public and yet allow maximum energy utilization of the wood resource for all market sectors.

The EPA, TVA, and DOE all recognized this need and, each has sponsored limited projects in this area. Central coordination of these projects on a federal level is needed. The DOE responsibility in this residential area lies within Consumer Products Branch of the Office of Buildings and Community Systems (TCP/BCS). They have the responsibility for developing technical programs in the areas of space heating and conditioning for residential and commercial buildings. Included in this mandate is the commercialization of residential and commercial wood burning systems.

---

* Butcher and Sorenson, Journal of the Air Pollution Control Association, Volume 29, No. 7, pp 724-728, July 1979.

** J. Cooper "Environmental Impact of Residential Wood Combustion Emissions and its Implications," Oregon Graduate Center for Study and Research (Presented at the Wood Energy Institute Wood Heating Seminar VI at Atlanta, Georgia, February 25-28, 1980).

John D. Ryan, the Residential Wood Program Manager within BSC/TCP convened a meeting to discuss residential wood emissions. The purpose of the meeting was to develop a consensus of emissions oriented technology needs in preparation for the development of a DOE program.

The meeting was held at Battelle, Columbus Laboratories on March 27-28, 1980. The 30 invited attendees (Attachment A) included representatives from the DOE, EPA, TVA, the Canadian Government, and researchers active in the field. The results of the sessions were definitive recommendations for needed technology effort in the areas of combustion, emissions, equipment development and improvement, and air quality. In addition, three of the four groups (combustion, emissions, and equipment) recommended the size and content of specific projects including the funding and manpower requirements. The recommended tasks and required funding to meet the needs defined by this "Tri Group" (combustion, emissions, and equipment) were reviewed by PYROS, Inc. and combined in this document. Multi-year program recommendations extending through FY 85 were thereby developed. These encompass 13 tasks and would require approximately $4 million in FY 81 to implement.

On the order of 50 scientific staff with a wide range of disciplines will be required to conduct such a program. This staffing requirement clearly indicates that the projects must be dispersed over a number of research organizations. The size of the program also indicates that in all likelihood, any federal government program to vigorously address the environmental area for wood will need the involvement and cooperation of all potential sponsoring organizations (i.e., EPA, TVA, DOE, Canadian Government).

Also strongly indicated is the value of a closely coordinated federal program which utilizes the management and scientific skills of the DOE, EPA and TVA organizations. This cooperation among the government sponsoring agencies was initiated at the "think shop" and is being pursued in parallel with technical program development.

The programmatic recommendations developed by the working groups are the actions solely of the members. The combining of these recommendations into a single group of recommendations are the result of PYROS' review and studies.* The technical contents and budgetary estimates contained in this report therefore do not necessarily reflect the intent of any government agency and are meant to be used for internal program planning within BCS/TCP.

The remainder of the paper describes the meetings, the actions of the committees and the recommendations resulting therefrom.

---

* This paper is a condensation of PYROS, Inc. Report 1011.R1, dated August 1, 1980 prepared for The National Bureau of Standards under Contract Number NB80NAAE6284

Mr. John M. Allen
Battelle, Columbus Laboratories
Columbus, Ohio 43201

Mr. Henry Anderson
Technology & Consumer Products Branch
U.S. Department of Energy

Mr. Charles Bendersky
PYROS, Inc.
Gaithersburg, Maryland 20760

Mr. Ron Bratten
Canada Combustion Research Lab
Ottawa, Canada K1A 0G1

Ms. Danelle Capozzi, Coordinator
PYROS, Inc.

Dr. Robert Cassanova
Georgia Institute of Technology
Atlanta, Georgia 30332

Dr. Han Chang
Argonne National Laboratory

Dr. John Cooper
Oregon Grad. Center for Study & Research
Beaverton, Oregon 97005

Dr. Gregory J. D'Alessio
Office of Environment
U.S. Department of Energy

Mr. Jimmie Dollard
Wood Commercialization Manager
U.S. Department of Energy

Dr. Charles Dudney
Health & Safety Research Division
Oak Ridge National Laboratory

Mr. J. Ernest Dunwoody
Mittelhauser Corporation
Washington, D.C. 20001

Dr. William L. Earl
Center for Fire Research
National Bureau of Standards

Dr. Earl W. Evans
Environmental Health & Safety Division
Pittsburgh Energy Technology Center

Mr. Robert C. Farley
SERI
Golden, Colorado 80401

Dr. Richard G. Gann, Head
Center for Fire Research
National Bureau of Standards

Dr. Wayne H. Griest
Analytical Chemistry Division
Oak Ridge National Laboratory

Mr. Robert E. Hall
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

Dr. John Harkness
Argonne National Laboratory

Dr. Jerome Harper
Tennessee Valley Authority
Chattanooga, Tennessee 37402

Dr. Colin J. High
Dartmouth College
Hanover, New Hampshire 03755

Dr. David C. Junge
Oregon State University
Corvallis, Oregon 97331

Mr. Lawrence Krupnak
Mitre Corporation
McLean, Virginia 22102

Mr. Arthur Levy
Battelle, Columbus Laboratories

Dr. Timothy Maxwell
Auburn University
Auburn, Alabama 36830

Mr. Gary J. Mihlan
Battelle, Columbus Laboratories

Mr. Mike Osborne
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

Dr. Dave Palmer
SERI
Golden, Colorado 80401

Mr. Wade H. Ponder
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

Mr. John Ryan
Technology & Consumer Products Branch
U.S. Department of Energy

Dr. Jay W. Shelton, Director
Shelton Wood Energy Research
Santa Fe, New Mexico 87502

Dr. Philip Sticksel
Battelle, Columbus Laboratories

ATTACHMENT A - ATTENDANCE LIST

PROCEEDINGS OF THE MEETING

FORMAT OF THE MEETING

The meeting started with the group of informal mini-presentations listed below.

A. Overview of Wood Commercialization Program
   Jimmie Dollard, Department of Energy

B. Statement of Purpose and Technical Overview
   John D. Ryan, Department of Energy

C. Regulatory Background and Environmental Impact of Residential Wood Combustion Emissions
   John Cooper, Oregon Graduate Center for Study and Research

D. State-of-the-Art Summary of Stoves
   John Allen, Battelle, Columbus Laboratories

E. Emissions Technology and Operational Effects
   John Harkness, Argonne National Laboratory

F. Diesel Particulates and Coal Emissions
   Earl Evans, Pittsburgh Energy Technology Center

G. State-of-the-Art of Emissions Control Technology for Industrial Combustion Systems Fired With Wood and Bark Residue Fuels
   David Junge, Oregon State University

H. Equipment Overview and Hardware Types
   Timothy Maxwell, Auburn University

I. Combustion Process Research (Phenomenological)
   William Earl, National Bureau of Standards

J. Instrumentation State-of-the-Art
   Robert Cassanova, Georgia Institute of Technology

K. Behavior Modification for Emissions Reduction
   Colin High, Dartmouth College

The above presentations addressed the role of government and provided state-of-the-art updates in residential combustion, industrial wood combustion, diesel and coal emissions and other topics thus bringing into focus all aspects of the total problem and technologies related to the problem.

Mr. J. D. Ryan, the DOE Residential Wood Program Manager, then organized the participants into four working groups having assessment functions in the areas for:

Combustion

Equipment

Emissions

Air Quality

Mr. Ryan selected a Moderator and a Secretary to head each group. The Moderator was responsible for focussing the input and developing a format which would adequately express the consensus: The Secretary was responsible for recording the proceedings and the preparation of a "group" working paper.

Figure 1 describes the organization, the constituents, and lists the technical issues to be considered by each group. The "shopping lists" of technical issues in several cases have redundant items that are relevant to the output of more than one of the groups. The membership of each group was primarily based on the technical interest of the attendees. However, in many cases, attendees "floated" into and participated in the work of more than one group. Thus, there was a constant cross-fertilization. After individual discussions with Mr. Ryan, the groups adjourned. The chairmen then prepared their results and mailed them to Mr. Ryan.

WORKING GROUP OUTPUTS

The outputs of each of the four working groups were provided in the form of separate reports which are included as part of the full report. They are individually summarized below.*

COMBUSTION GROUP

The Combustion Group concentrated on the following items: basic combustion chemistry, pollutant formation, combustion modifications that influence emission production, and fuel variability and was able to define an emissions oriented program which identified and ranked the research needs and established types and numbers of technical manpower requirements.

The tasks were divided into the seven following areas as shown in Figure 2:

Performance Efficiency

Pollutant Formation

Combustion Modification

Fuel Variability

Creosote (Emissions Related)

Cyclic Operation

Additives

An eighth area "Supporting Combustion Research" was later defined.

---

* The Combustion, Equipment, and the Emissions group each developed separate work breakdown structures and budgetary estimates for its technical area. These are omitted from this paper but are included in the full report.

- Chairman: John D. Ryan, BCS/TCP (DOE)
  Henry Anderson, BCS/TCP

Equipment	Combustion	Emissions	Air Quality
Moderator: R. C. Farley	Moderator: A. Levy	Moderator: J. Harkness	Moderator: D. Junge
Secretary: J. E. Dunwoody	Secretary: B. Earl	Secretary: D. Palmer	Secretary: L. Krupnak
J. M. Allen R. Braaten H. Chang J. Harper T. Maxwell J. W. Shelton	C. Bendersky R. Cassanova R. G. Gann R. E. Hall	E. W. Evans W. H. Griest J. Harper W. H. Ponder	J. Cooper J. Dollard C. Dudney C. J. High G. J. Mihlan M. Osborne P. Sticksel
Charges:			
Design & Operation Control Technology Cost Effectiveness Control Levels vs. Action Standards Reliability Safety Fuel Variability	Basic Combustion Chemistry Pollution Formation Combustion Modification Fuel Variability	Species Measurement Sampling Creosote Combustion Modification Quantitative Goals Bioscreening Indoor	Dispersion Health Effects Measurement Regulation Density Indoor/Outdoor

Figure 1. Constitution and Membership of Residential Emissions Think Shop Groups

	Present Technical Status	Priority			FY 81 Start	
		Research Input Need	Probability of Success in 4 Yrs.	Value of Success	Man-Yrs./Yr.	Total Yrs. Of Project
Performance (efficiency)	Good	Small	--	—	0	0
Pollutant formation	Poor	High	High	Very High	6	3
Combustion modification	Poor	(3)[+] NOX (3) CO (1) POM (2) Aldehydes (2) Unsat. Combust. (1) Particulates	High	High	6/2*	4 (Continuous work)
Fuel variability	Fair	High	Very High	High	1/2*	1-2
Creosote	Poor	High	Good	Very High	2/2*	4 (Continuous work)
Operation (cyclic pollution)	Fair	High	High	Mod.	2	2
Additives	Poor	?	Poor	High	1	2

Effort: Total Program ≈ 12-17 man-yrs./yr.
Organizations participating, 2-6

* = Two independent laboratories.

+ = ( ) Numbers are priority, low is highest.

Figure 2. Combustion Group - Research Needs Assessment

The conclusions of the group are summarized as follows:

1. There is presently little known about the combustion of wood in realistic stove type fires.

2. A standardized test procedure and fuel(s) must be developed early in the program. All standardized testing is now done using "cribs" made of kiln dried arrays called brands. It was recognized that a new standardized fuel must be developed that accurately represents bark and wood type, size, wetness, etc. encountered in realistic field conditions. In addition, work must be undertaken in the areas of processed fuels, i.e., pellets, chips, etc. The standardized test procedure must allow easy interrelationship between supporting combustion research, combustion testing, and equipment development. Necessary relationships with safety and efficiency test procedures also need to be established.

3. The identified biggest problem in conducting the programs will be in the area of accurate sampling techniques.

4. A key research need is in the area of smoke and particulate formation and traverse through an appliance. Recognized testing, sampling, and measurement procedures which can be applied to this subject may not be available.

EQUIPMENT GROUP

The Equipment Group concentrated on product development and sales issues for stoves and other more sophisticated types of residential space heating systems. The emphasis was on hardware, not technology. The group attempted to answer the question, "If a complete, better, and probably more costly line of equipment were available, what improvements would be included and would the consumers be motivated to buy the better equipment?" In addition, the consideration of "restrictive growth or usage within particular air sheds" was discussed.*

As a result, the group developed a matrix of independent technology actions which were discussed and evaluated against "market impact" for both the near term (by 1983) and the far term (by 1985) (Figure 3).

The Equipment Group defined the need for the seven tasks listed below:

Characterization of Existing and Future Equipment Performance

Dissemination of Results of Present and Future Equipment Performance Characteristics

Processed Wood Fuel Development and Utilization

---

* Some air sheds are approaching or exceeding environmental limitations now. New emitters will compete with existing installations for operating permits.

	Market Impact						Total	
	Cost	Consumer Acceptance	Need Near*	Need Far*	Emissions Reduction	Efficiency	Near Term	Far Term
I. Fuel Rate-Limited Combustion	1	2.5	1	3	3	3	10.5	12.5
II. Thermal Energy Storage	1	2	1	3	3	2	9	11
III. Stack Clean-up Technology								
a. Removal Systems	1	1	1	2	1	1	5	6
b. Conversion Systems	2	1	1	2	3	2	9	10
IV. Improved Combustion								
a. Catalytic Combustion	2	3	1	3	2	2	10	12
b. Enhanced Secondary Combustion	3	3	3	3	2	2	13	13
c. Geometry of Combustion Chamber	3	3	3	3	1	1	11	11
d. Air-tightness Reduction	3	1	3	3	2	1	10	10
e. Insulated Combustion Chamber	2	3	1.5	2.5	2	2	10.5	11.5
f. Forced Combustion Air	2	2	2	3	2	2	10	11
g. Heated Secondary Air	2	3	1	1	1.5	1.5	9	9
h. Heated Combustion Air	2	3	1	1	1	1	8	8
i. Heat Exchanger Design	2	2	2	3	1.5	3	10.5	11.5
V. Improved Fuels - Feasibility Study	2	2	1	3	3	2	10	12

* Near Term: by 1983
* Far Term: by 1985

Key:
1 = Not favorable
2 = Moderate
3 = Favorable

Figure 3. Equipment Group - Technology Actions Assessment

Application of Energy Storage Technology to Wood-Burning Appliances

Application of Heat Exchanger Technology to Wood-Burning Appliances

Develop Emissions Clean-Up Technology for Wood-Burning Appliances

Parametric Investigations and Demonstrations of Combustion Improvement Techniques for Wood-Burning Appliances

The single most urgent need identified by the Equipment Group was for early development of a standardized testing procedure and measurement techniques for both efficiency and emissions.

EMISSIONS GROUP

The Emissions Group focused primarily on questions concerning the measurement of point source emissions from residential wood burning systems, defined to be stoves plus chimney systems. The group realized that different types of chimney systems affect the stove emissions and the group agreed that, at some point, stove emissions should be determined independently of chimney effects. However, the overriding concern today is with the overall implications of wood burning emissions for air quality, ecological effects, and health effects. The emissions testing task is crucial to the improved understanding of these implications whether they are projections based on dispersion models or interpolations based on receptor models. Likewise, emissions testing must be closely coordinated with combustion studies and equipment development activities to insure that realistic emission tests are performed. Tests must represent actual stove usage and must study the proper combustion system variables. Emission testing and combustion studies will very likely be carried out concurrently within individual experimental programs. However, the equipment development activities are more likely to be separate and, therefore, more dependent on feedback from the combustion and emissions studies.

The group established the ranking of system emission concerns and priorities for "regulators, manufacturers, and users" as shown in Figure 4. The key concern was outdoor airborne emissions and the key technology need was development of a standardized wood burning stove rating test. The required capability of the test method was stated as follows:

> "The test should be a credible, relatively simple version of the laboratory tests developed to measure specific emissions factors. The test must be repeatable within individual laboratories as well as between laboratories. The test should probably be developed in two stages with an interim, qualitative test ready within a year to rate stoves by "high" "average" or "low" emissions. This would be followed by an industry standard which would be capable of testing stoves for meeting specific emission standards."

Emission Concerns	"Regulators"	Manufacturers	Users
I. Emissions Testing			
A. Emissions			
Outdoor Airborne	I	IIa	IIIa
Indoor Airborne	-	III	II
Creosote	-	(IIb Safety)	IIIb
Ash	-	-	-
B. Issues/Concerns			
Emission Rates	IIa	-	-
Emission Activities	IIb	-	-
Emission Factors	V	-	-
Identification of Emissions	-	-	-
II. Sampling and Analysis			
A. Sampling	IV	-	-
B. Sampling Methods	IV	-	-
C. Analytical Techniques	IV	-	-
III. Development of Stove Rating Test	III	I	I

---

[1] Note: (-) indicates low priority.

Figure 4. Emissions Group - Systems Emissions Assessments

The following three tasks were defined:

Stove Test Development

Characterization and Measurements of Stove Emissions

Sampling and Analytical Development

The stove test development is an expansion of the first task specified by the Equipment Group.

Research needs were detailed relating to the quantification of the emittants and sampling and analysis procedures. Existing measurements of the species, forms, etc. were stated to have shown poor experimental reproducibility which may preclude projection of credible local and/or regional air quality impacts from wood burning. A special concern is the inability to define respirable particulates in terms of particle size distribution and content of cancer precursor types of compounds (POM).

The principal concern in sampling and analyses is that many of the accepted sampling methods (EPA-5, EPA-17, or SASS) are believed to be not entirely appropriate in this program. Several modifications to these techniques are being used by various experimenters which could lead to a proliferation of non-standard systems. The group concurred that modifications to the standard systems will be required but that these must be "standardized" for use by all experimenters and data gatherers. The present measurement techniques are "batch" types with analyses performed on samples collected in situ, or shorter cycle batch time sampling procedures was indicated.

In the health affects area, it was concluded that the spot tests for POM's developed by A. D. Little may in some cases provide erroneous results and the AMES test should be fine-tuned for applicability to wood emissions.

AIR QUALITY GROUP

The Air Quality Group focussed on the environmental effects to three market sectors: (1) the regulators, (2) the equipment manufacturers, and (3) the consumers. Their conclusions are summarized in Figure 5.

The issues were discussed in terms of;

What is an acceptable AQ level?

Dispersion

Secondary (or indirect) impacts on other sources

Health effects

Identification of tracer (or surrogate) pollutants

Assessment of the magnitude of effects (present or predicted)

Measurement techniques (ambient air emissions)

Indoor effects

ISSUE: AIR QUALITY (AQ)	MARKET SECTOR		
	EPA[1]	MANUFACTURERS	CONSUMERS
What is an acceptable AQ level?	X	X	X
Dispersion	X	X	X
Secondary (or indirect) impacts on other sources	*6	X	X
Health effects	*2	X	*2a
Identification of tracer (or surrogate) pollutants	*1c	X	X
Assessment of the magnitude of effects (present and predicted)	*1a	*3	*2b
Measurement techniques (ambient air emissions)	*1b	X	X
Indoor effects	*7Ø	*5	*3
Incentives (regulations, tax breaks, safety, permits, cost-effectiveness)	*4	*2	*1a
Allowable population density of "classes" of woodburning stoves	*3	*1	*1b
Education and understanding of trade-offs	*5	*4	*2

NOTES: Ø = Based on present level of information
X = Not a major immediate concern
* = Requires immediate understanding

[1] EPA MARKET SECTOR INCLUDES ALL REGULATORY AGENCIES INVOLVED, FEDERAL, STATE, LOCAL.

Figure 5. Air Quality Group - Emissions Assessments

Incentives (regulations, tax breaks, safety, permits, cost-effectiveness)

Allowable population density of "classes" of wood burning stoves

Education and understanding of trade-offs

The Air Quality Group developed a large number of suggested actions which are preliminary indicators of work breakdown structures. (They did not choose to develop tasks suitable for budgetary estimating.) PYROS rearranged these into a group of 11 assessment studies, educational (commercialization) actions, and research activities. See the full NBS report for the description of these actions.

COMBINED OUTPUTS

The study groups transmitted their outputs to the DOE Think Shop Chairman who then directed PYROS, Inc. to digest, combine, and summarize the recommendations. The overall recommended program is planned for completion by the beginning of FY 85 as market penetration of the "First" generation of equipment will have been largely completed by this time.

Conceptual definition of the total program was developed using the "events" flowsheet shown in Figure 6.* By FY 81, projects should be underway in five areas; air quality, emissions measurements, combustion testing, equipment development, and supporting technology. These include field air shed measurements for the air quality activity; field source measurements, laboratory source measurements at all locations in the stack, sampling and analytical techniques development for emissions measurements activities; pollutant formation studies as functions of stove operating conditions for the combustion activity; clean up hardware and stove test development for the equipment activity. A vigorous supporting technology activity should be in progress concentrating on smoke and particulate formation, wood pyrolysis and internal aerothermodynamics. Key milestones will occur in early FY 82. An interim assessment of air quality and health impacts will be completed and a standard interim stove test will be specified. The stove test is very important as it should immediately affect the regulatory and manufacturing sectors. The flow of the activities continue. The standard stove test will be specified in mid FY 83. Using that test, emissions goal recommendations and final air quality assessments would be available by FY 84.

In the following sections, the work breakdown and budgetary outputs of the groups are melded together into one composite program.

WORK BREAKDOWN STRUCTURE

The Combustion, Equipment, and Emissions Groups developed tasks which included budgetary and manpower estimates which were carefully analyzed. It became evident that they could be divided into two categories: "research" and "commercialization". The "research" tasks are those which require sophisticated scientific approaches and highly specialized investigators; the

---

* The format of and most of the contents of the Program Flowsheet shown in Figure 6 is the contribution of Dr. John Harkness, of Argonne National Laboratories, the Emissions Group Coordinator.

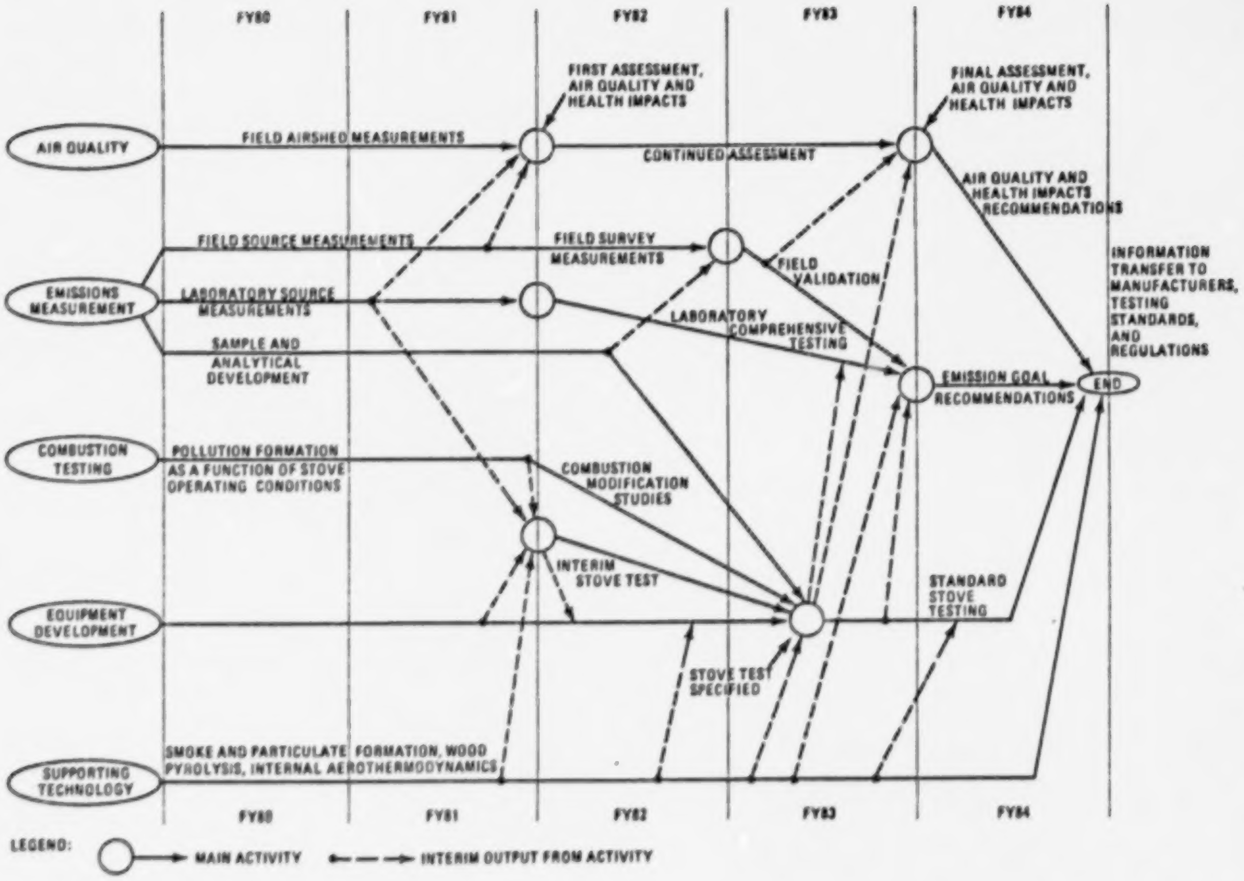

FY80
FY81
FY82
FY83
FY84
AIR QUALITY
EMISSIONS MEASUREMENT
COMBUSTION TESTING
EQUIPMENT DEVELOPMENT
SUPPORTING TECHNOLOGY
FIELD AIRSHED MEASUREMENTS
FIRST ASSESSMENT, AIR QUALITY AND HEALTH IMPACTS
CONTINUED ASSESSMENT
FINAL ASSESSMENT, AIR QUALITY AND HEALTH IMPACTS
AIR QUALITY AND HEALTH IMPACTS RECOMMENDATIONS
FIELD SOURCE MEASUREMENTS
FIELD SURVEY MEASUREMENTS
FIELD VALIDATION
LABORATORY SOURCE MEASUREMENTS
LABORATORY COMPREHENSIVE TESTING
SAMPLE AND ANALYTICAL DEVELOPMENT
EMISSION GOAL RECOMMENDATIONS
END
INFORMATION TRANSFER TO MANUFACTURERS, TESTING STANDARDS, AND REGULATIONS
POLLUTION FORMATION AS A FUNCTION OF STOVE OPERATING CONDITIONS
COMBUSTION MODIFICATION STUDIES
INTERIM STOVE TEST
STOVE TEST SPECIFIED
STANDARD STOVE TESTING
SMOKE AND PARTICULATE FORMATION, WOOD PYROLYSIS, INTERNAL AEROTHERMODYNAMICS
LEGEND:
MAIN ACTIVITY
INTERIM OUTPUT FROM ACTIVITY

Figure 6. Program Flowsheet: Events Impacting the Emissions Program

"commercialization" tasks are those which are primarily technology transfer activities, those which require incorporation of existing technologies into furnace systems, or projects which primarily support direct product developments. Thus, in the Emissions Group recommendations the "Consumer, Manufacturer Information" task supports technology transfer needs while both the "Energy Storage", and "Heat Exchanger Technology" tasks incorporate existing technology into furnaces. Table 1, parts A, B, and C summarize the combined tasks including budgetary and manpower estimates recommended by the Combustion, Equipment, and Emissions (Tri) Groups. Table 1A summarizes the total output, Table 1B the commercialization tasks, and Table 1C the research tasks. The costs are based on $100 K per scientific man year. Special test equipment or capital equipment requirements are not included. The group(s) which suggested the individual tasks are identified in Tables 1B and 1C.

Commercialization Tasks

Four commercialization tasks were suggested (Table 1B). Full implementation of these tasks in FY 81 would require $700 K. The consumer/manufacturer and processed fuel development and utilization activities would extend over the life of the program while the product development task (which combines the energy storage and heat exchanger tasks) and the fuel variability and cyclic operation work would be of a shorter two year duration.

Research Tasks

Nine research tasks were suggested (Table 1C). Task 1 "Stove Test Development and Test Procedures" combines the recommendations of the Emissions and Equipment Groups and will satisfy the needs identified by the other two groups. Similarly, Task 7 "Combustion Processes; Parametric Studies and Demonstrations" combines the recommendations of the Equipment and Combustion Groups, includes the emissions oriented creosote work, and will satisfy the needs of the other two groups. Task 9 "Supporting Combustion Research" requires two or more separate efforts to satisfy the needs addressed. It is noted that the research needs in "Fuel Variability and Cyclic Operation" identified by the Combustion Groups are not specifically identified and were assumed to be integrated into the Task 5 "Pollutant Formation" studies.

As shown in Table 1C, some work is underway in FY 80. Specifically, pollutant and combustion processes studies are underway at Auburn University, Battelle Columbus Laboratories, and Argonne National Laboratories. Full implementation of the recommended program in FY 81 would require $3.3 million. The Task 8 "Additives" activity is a short term screening program which must be accompanied by a PON type of solicitation to obtain candidate "additives" for evaluation. Similarly, the Task 3 "Sampling and Analytical Development" and the Task 4 "Emissions Clean Up Technology" projects must be short term intense programs to be of programmatic value. The remainder of the tasks probably could be completed with the indicated FY 84 funding level; however, the FY 85 funding recommendations represents program wind-down.

Total Program

The total resource and manpower estimates are displayed in Table 1A. These resources are to conduct actual projects and do not include funds for

TABLE 1A

EMISSIONS THINK SHOP

SUMMARY OF TRI (COMBUSTION, EQUIPMENT, EMISSIONS) GROUP RECOMMENDATIONS[1]

Costs in $1000

	Fiscal Year					
BUDGET AND MANPOWER REQUIREMENTS	80	81	82	83	84	85
A. Totals						
1. Financial						
Commercialization Tasks (4)	-	700	1100	350	200	200
Research Tasks (9)	400	3300	3650	3100	2100	900
Total $1000	400	4000	4750	3450	2300	1100
2. Scientific Personnel						
Commercialization Tasks	-	7	11	3.5	2	2
Research Tasks	4	33	36.5	31	21	9
Total Man Years	4	40	47.5	34.5	23	11

---

[1] Based on 1980 Costs of $100,000 Per Man Year of Scientific Personnel

TABLE 1B

EMISSIONS THINK SHOP

SUMMARY OF TRI (COMBUSTION, EQUIPMENT, EMISSIONS) GROUP RECOMMENDATIONS[1]

TASKS	Group	81	82	83	84	85
B. Commercialization Tasks						
1. Consumer/Manufacturer Information	Equip.	100	150	150	100	100
2. Processed Fuel Devel. & Util.	Equip.	150	300	200	100	100
3. Product Development (Energy Storage & Heat Exchanger)	Equip.	200	400			
4. Fuel Variability & Cyclic Operation	Combust.	250	250			
Total ($1000)		700	1100	350	200	200
Equivalent Scientific Man Years		7	11	3.5	2	2

---

[1] Based on 1980 Cost of $100,000 Per Man Year of Scientific Personnel

TABLE 1C

EMISSIONS THINK SHOP

SUMMARY OF TRI (COMBUSTION, EQUIPMENT, EMISSIONS) GROUP RECOMMENDATIONS[1]

TASKS	Group	80	81	82	83	84	85
C. Research Tasks							
1. Stove Test Devel. & Test Procedures	Emiss. & Equip.	- -	500 200	500 200	200 100	200 100	200 100
2. Characterization and Measurement of Stove Emissions	Emiss.	-	500	500	600	400	200
3. Sampling & Analytical Development	Emiss.	-	150	150	100	-	-
4. Emissions Clean Up Technology	Equip.	-	150	100	-	-	-
5. Pollutant Formation	Comb.	300	300	600	600	300	-
6. Combustion Modification	Comb.	-	600	600	600	300	-
7. Combustion Processes Parametric Studies and Demonstrations (Includes Creosote)	Equip. & Comb.	100	400	500	500	400	200
8. Additives	Comb.	-	100	100	-	-	-
9. Supporting Combustion Research	Comb.	-	400	400	400	400	200
Total R&D ($ K)		400	3300	3650	3100	2100	900
Equivalent Scientific Man Years		4	33	36.5	31	21	9

---

[1] Based on 1980 Cost of $100,000 Per Man Year of Scientific Personnel

DOE (or other agency) program management support either at headquarters or at field centers. Full implementation of the recommended program in FY 81 would require $4 million and 40 man years of scientific personnel. The nature of the programs dictate the labor intensity. Discussions at the "think shop" clearly showed that there were probably an insufficient number of scientists trained in the appropriate disciplines who could be brought to bear on the research without involving several well rounded scientific organizations.

PROGRAMMATIC PRIORITIES

PYROS assigned the following priorities for addressing the technical needs for a residential wood emissions program:

(1) Develop a standard stove testing technique for laboratory source measurements. This is the most urgent priority.

(2) Develop a data base on pollutant formation as a function of stove type and operating conditions. This program has started at Auburn University and at Battelle, Columbus Laboratories.

(3) Review the accepted sampling techniques and proposed modifications thereto; and, then recommend and substantiate reproducibility of proposed new techniques (i.e., EPA-5, EPA-17, SASS).

(4) Initiate a vigorous supporting combustion research program in the areas of smoke and particulate formation, combustion aerothermodynamics within the chamber/stack, etc.

(5) Develop and implement a program to obtain field air shed measurements specifically relating to residential wood outputs.

CONCLUDING REMARKS

The Residential Emissions Think Shop was clearly an important milestone in the efforts to accelerate the use of wood for energy. The attendees included the key DOE, EPA, TVA, and the Canadian Government program managers, scientists and program managers from the key government laboratories, and the active industrial and university principal scientists in this field. Some federally funded programs have been initiated in this area prior to FY 80.* These actually have been gentle probes in areas of combustion, pollutant identification, and air quality at very modest funding levels. Probably less than $300,000 was spent on residential wood emissions prior to FY 79. In FY 80, tasks in pollutant identification were initiated or underway at Auburn University (DOE), Argonne National Laboratories (DOE), Battelle, Columbus Laboratories (EPA/TVA), TRW, Inc., EPA and others. It was immediately established that these efforts merely scratched the surface. The recommended technical program developed in this "think shop" will require approximately $4 million dollars** in FY 81 to implement. This is an order of magnitude above last years expenditures in the area. Possibly a greater restraint on program implementation than funding is the need to have the skills of approximately 40 scientists applied directly to the projects. These skills encompass the fields of combustion, physics, environmental sciences, health affects, chemistry, etc. and require specially trained personnel to operate the sophisticated measurement devices. Limited amounts of specialized skills and equipment do exist at facilities such as Battelle, Monsanto, the National Bureau of Standards, Argonne National Laboratories, Oak Ridge National Laboratories, the Georgia Institute of Technology, the Pittsburgh Energy Technology Center (DOE), and others. Most are fully employed on other equally high priority projects.

---

* An excellent survey of the topic of health effects is contained in the recent DOE report: G. J. Allessio (DOE) and R. E. Kawaoha, "Health Effects of Residential Wood Combustion Survey of Knowledge and Research", The Aerospace Corporation, March 1980.

** This does not include air shed measurements.

It is doubtful that the required number of high caliber personnel can be made available at any one or even two or three facilities. The staffing requirement clearly indicates that the projects must be dispersed over a number of participating research organizations and strongly indicates the value of a coordinated federal program which could utilize the management and scientific skills of the DOE, EPA, and TVA organizations.

OVERVIEW OF EMISSIONS FROM WOOD COMBUSTION

By:

K. J. Lim and H. I. Lips
Energy & Environmental Division
Acurex Corporation
Mountain View, California 94047

ABSTRACT

An assessment is made of emissions and their control from wood-fired boilers, home stoves, and fireplaces. The major pollutants are particulates, hydrocarbon (including organics), and carbon monoxide; nitrogen oxides are also emitted. Although the data base is limited and diverse, the important parameters affecting emissions appear to be combustor design, excess air level, and burning rate. For boilers, optimal emissions control and efficiency are achieved with 50 to 200 percent excess air, with overfire air maximized for stokers. Data on other combustion modification techniques and operational impacts are minimal. On a normalized basis, residential wood-burning units tend to produce higher emissions than do boilers. Data on wood-fired stoves indicate that certain designs, e.g., crossdraft, emit less particulate matter. The limited data suggest that the low burning rates, typical of home stoves, are conducive to POM formation, a pollutant of major concern. As the combustion conditions for fireplaces are even more difficult to quantify and control, emission trends for those devices are less well established. However, POM emissions appear to be lower from fireplaces than from stoves.

INTRODUCTION

The recent revival of wood as a primary or alternate source of energy, along with mounting evidence that wood combustion can produce disproportionately high emissions of hazardous pollutants, has raised many environmental concerns. In this era of escalating fossil-fuel costs, wood is rapidly gaining favor as a renewable and dependable alternate energy source. Indeed the U.S. Department of Energy is actively encouraging the expansion of wood utilization in the industrial, utility, and residential sectors (1).

Because of the high moisture and low heating value of wood, wood is an economically attractive fuel only on a regional or local basis, close to areas of heavy forestation, due to high transportation costs. And it is the resultant regional or local concentration of wood combustion emissions that can contribute to ambient air quality problems, especially from the residential sector (2).

Emissions from wood combustion and associated air quality impacts have only recently been the subject of intensive investigation (2). A wide range of emission rates has been reported; many results are not comparable because operating conditions were not equivalent. However, the limited data do indicate that wood fuel produces negligible SO_2 and low NO_x emissions as expected. But particulate, CO, and hydrocarbon (including organic) emissions are of concern. There has been some evidence that a particular class of organic compounds, polycyclic organic matter (POM), some of which are potentially carcinogenic, may be emitted in significant quantities, especially from residential wood combustion equipment.

Given this background of increasing wood utilization, and possible adverse environmental impacts, there is a need to assess and correlate if possible the scattered research results that have been produced to date. This paper is a summary of such a study sponsored by EPA (3). The objective of that study was to review and assess the existing data base on residential and industrial wood combustion emissions so as to identify potential emissions problems and evaluate the effect of combustion modifications on emissions.

WOOD COMBUSTION SOURCE CATEGORY

Wood as Fuel

Biomass currently supplies nearly 2 percent of U.S. energy consumption (or about 1.6 EJ/hr), primarily from the use of wood in the forest products industry and in home heating (4). Wood has been projected to supply as high as 5 to 10 percent of the year 2000 energy needs (4, 5).

Wood generally contains 45 to 65 percent moisture (wet basis) as delivered. In residential use, wood is often "seasoned" or dried to about 20 percent moisture prior to burning. Hogged fuel -- a mixture of mechanically chipped wood and bark generally used in industrial wood combustors -- normally contains 45 to 55 percent moisture (6). The high moisture content of wood, as compared to other solid fuels such as coal, is a major cause of the lower overall thermal efficiency of industrial wood combustors (65 to 78 percent) as compared to that of coal combustors (up to 88 percent) (7). Furthermore, the weight of the water limits the economic feasibility of wood combustion to local use, say within 50 to 200 miles of the source (1, 8, 9). Finally, high moisture content can lead to incomplete combustion, increasing emissions of CO, unburned hydrocarbons, and soot.

The overall composition of wood is remarkably uniform. The high percentage of volatile matter (70 to 80 percent, dry) and low fixed carbon content (17 to 27 percent, dry) (6) incidate that it is relatively easy to ignite the fuel and sustain combustion. Table 1 shows representative ultimate analyses of wood and bark (10, 11). Wood contains relatively low ash, generally less than 1 percent, with bark containing possibly higher ash content, up to 5 percent, though still generally less than that of coal. The very low concentrations of fuel bound nitrogen and sulfur, generally 0.1 percent or less, indicate that the emission rates of the two criteria pollutants NO and SO_2 are expected to be low. This is a major factor in considering use of wood as an alternate fuel. Note, however, that although

TABLE 1. ULTIMATE ANALYSIS OF TYPICAL WOOD AND BARK, DRY (10, 11)

	Percent by Weight						Heating Value[a]	
	C	H	S	O	N	Ash	(kJ/kg)	(Btu/lb)
Softwoods								
Fir, Douglas	52.3	6.3	--	40.5	0.1	0.8	21,000	9,049
Pine, pitch	59.00	7.19	--	32.68	--	1.13	26.300	11,333
white	52.55	6.08	--	41.25	--	0.12	20,650	8,898
yellow	52.60	7.02	--	40.07	--	1.31	22,300	9,609
Redwood	53.5	5.9	--	40.3	0.1	0.2	20,510	8,838
Averages	53.0	6.4	--	39.8	--	0.8	21,650	9,329
Hardwoods								
Ash, white	49.73	6.93	--	43.04	--	0.3	20,700	8,920
Oak, black	48.78	6.09	--	44.98	--	0.15	19,000	8,187
red	49.49	6.62	--	43.74	--	0.15	20,200	8,704
white	50.44	6.59	--	42.73	--	0.24	20,400	8,791
Poplar	51.64	6.26	--	41.45	--	0.65	20,700	8,920
Averages	50.3	6.4	--	42.8	--	0.5	20,180	8,696
Bark								
Pine	53.4	5.6	0.1	37.9	0.1	2.9	21,000	9,049
Redwood	51.9	5.1	0.1	42.4	0.1	0.4	19,400	8,360
Oak	49.7	5.4	0.1	39.3	0.2	5.3	19,500	8,403
Averages	51.7	5.4	0.1	39.9	0.1	2.9	20,000	8,618

---

[a] Kiln dried wood assumed to contain 8 percent moisture.

fuel nitrogen content is low, NO_x formation from thermal fixation of nitrogen present in combustion air ("thermal NO_x") could still be significant.

Mineral constituents of wood vary greatly between species and between trees within a species. However, there does not appear to be any particular toxic elements such as lead or mercury. The major minerals are calcium, potassium, sodium, magnesium, phosphates, and silicates (10, 12).

Wood Combustion Equipment

Current and projected residential wood heating equipment types include fireplaces, stoves, and central furnaces. Fireplaces, with their low heating efficiency (generally less than 25 percent), are used mainly for aesthetic or auxiliary heating purposes, while wood stoves (50 to 70 percent efficient) are utilized for primary or zone heating. The highly labor-intensive activity associated with hand-fired central furnaces is expected to limit the appeal of these units (13).

The other major wood-burning sector is industrial process heat and steam production. The current and projected designs are spreader and inclined grate stoker boilers and suspension-fired boilers. Older designs such as dutch ovens and fuel cells with less operating flexibility or lower efficiency, are being phased out (1, 7, 14). A brief review of wood-fired industrial boiler designs as well as residential heating equipment is given in the EPA study (3).

RESIDENTIAL WOOD COMBUSTION EMISSIONS

The existing data base on residential wood combustion was surveyed and a number of key studies were reviewed (15-24) in detail in the EPA study (3).

Residential Emissions

Table 2 compares typical emissions from residential fireplaces, wood stoves, and conventional (non-controlled) distillate oil-and gas-fired furnaces (3). The emission rates indicated are typical or mean values; the numbers in parentheses show the broad range in reported values. It is of concern that the major pollutants from wood burning, -- CO, particulate, and total hydrocarbon emissions -- are significantly higher than those from conventional fuel-fired furnaces. And perhaps of greatest concern is the apparent high level of POM emissions (including the potential carcinogen, benzo(a)pyrene) from residential wood combustion. SO_2 emissions from wood burning are negligible as expected. NO_x emissions from residential wood combustion may be comparable to or larger than those from oil- or gas-fired systems. As noted earlier from the elemental composition of the low ash content of wood, bottom ash from wood combustors does not appear to be an environmental hazard.

NO_x emission from fireplaces and wood stoves appear to be comparable, though the hotter, more intensive flames in fireplaces would be expected to produce higher NO_x emissions. Although DeAgnelis, et al., (19), found about

TABLE 2. TYPICAL EMISSIONS FROM RESIDENTIAL FIREPLACES, WOOD STOVES, AND DISTILLATE OIL- AND GAS-FIRED FURNACES[a]

Pollutant	Fireplace		Stove		Oil Furnace	Gas Furnace
	g/kg	μg/J	g/kg	μg/J	μg/J	μg/J
NO_x	1.9(0.85-7.7)	0.12(0.05-0.5)	2.3(0.2-7.4)	0.15(0.01-0.5)	0.037-0.085	0.028-0.045
SO_2			0.2(0.16-0.24)	0.011(0.009-0.01)	0.022-0.22	--
CO	54(13-220)	3.4(0.8-14)	150(10-420)	9.7(0.6-30)	0.015-0.03	--
Particulate	15(1.8-64)	1.1(0.1-5)	13(1.3-45)	1.0(0.1-4)	0.008-0.03	0.009-0.025
Total Hydrocarbon	22(2.7-49)	1.6(0.2-4)	25(2.0-110)	1.9(0.1-8)	0.0002-0.003	0.00002-0.0002
POM	0.03(0.02-0.04)	0.002(0.001-0.003)	0.3(0.01-0.4)	0.02(0.001-0.03)	0.00001-0.00003	--
Trace Elements			~10^{-3} or less		~10^{-3} or less	--

[a] Emissions data compiled in reference 3.

TYPING GUIDE SHEET

three times higher NO_x from fireplaces than from stoves, the stove NO_x results of Allen and Cook (24) and Kosel, et al. (21), were comparable to those of DeAngelis, et al., for fireplaces.

CO emissions from stoves appear to be higher than those from fireplaces, as expected. The fireplace conditions with higher excess air, more turbulent mixing, and hotter flames lead to better CO burnout.

Particulate and POM emissions from residential wood combustion are of special concern, as they are almost entirely in the inhalable size range and contain a variety of toxic and irritating substances, including potential carcinogens (2). Table 3 reproduced from the work of DeAngelis, et al., shows the variety of POM emissions emitted (19). POM emissions from stoves are of the order of 0.3 g/kg of wood fired (0.02 g/J heat input). This level is about an order of magnitude greater than that from fireplaces. But the stove POM values measured by Allen and Cooke (24) averaged about 0.03 g/kg (0.01 to 0.05 g/kg range) or about 0.002 g/J which is much less than the results of DeAngelis, et al. Both sets of tests were conducted at fuel feed rates of about 0.12 to 0.18 kg/min, which is probably at a larger load than most wood stoves would normally be operated. There were no apparent reasons for the differences in the data.

To help evaluate the potential health hazards of residential wood combustion emissions, DeAngelis et al., subjected their fireplace and stove effluent samples to a battery of health- and ecological-based bioassays (19). The flue gas samples showed mutagenic activity, with the organic extracts more toxic than the particulate catch extracts and the stove samples more toxic than fireplace samples. Bottom ash samples showed no mutagenic activity, and low or nondetectable toxicity responses.

Effect of Equipment Design and Combustion Conditions

Before discussing the effect of combustion conditions on fireplace and wood stove emissions, several comments should be made. First, the equipment is difficult to fine tune and the user is generally not a trained operator. Also because of the small size of the combustors, the low flue gas flow rates, and the many types, sizes, and methods of firing the wood, exact quantitative measurements are hard to make. Thus, only overall gross effects can be studied as possible techniques to reduce emissions. Because of the difficult nature of residential wood heating emissions characterization, the results measured by different experimentalists are often contradictory.

Fireplaces

Experience with operational modifications to reduce emissions from fireplaces is limited. The limited data indicate a slight tendency for lower emissions when operating under lower excess air. But there were also test points where the opposite occurred and lower excess air increased emissions. Higher burning rates also showed a slight tendency to produce less emissions on a normalized g/kg basis, but total emissions may still be greater if more wood is burned. More tests are needed before definite guidelines on fireplace operation can be given.

TABLE 3. POM EMISSIONS (g/kg) (19)

	Fireplace			Baffled stove		Nonbaffled stove		
	Seasoned oak		Green pine	Seasoned oak	Seasoned pine	Seasoned oak	Green pine	
POM compounds	POM train	SASS train	POM train	POM train	POM train	POM train	POM train	SASS train
Anthracene/phenanthrene	0.0082	0.0114	0.0069	0.0745	0.1463	0.0618	0.1034	0.0104
Methyl-anthracenes/-phenanthrenes	0.0027	0.0034	0.0083	0.0211	0.0510	0.0167	0.0513	0.0028
C_2-alkyl-anthracenes/-phenanthrenes	<0.0014[a]	0.0011	0.0014	0.0040	0.0070	0.0045	0.0094	0.0008
Cyclopenta-anthracenes/-phenanthrenes	<0.0014[a]	0.0004	0.0014	0.0032	0.0086	0.0030	0.0047	0.0002
Fluoranthene	<o.0014[a]	0.0026	0.0016	0.0180	0.0316	0.0208	0.0188	0.0012
Pyrene	<0.0014[a]	0.0026	0.0016	0.0156	0.0240	0.0169	0.0188	0.0013
Methyl-fluoranthenes/-pyrenes	<0.0014[a]	0.0023	0.0016	0.0128	0.0167	0.0103	0.0142	0.0016
Benzo(ghi)fluoranthene		0.0009	0.0014	0.0048	0.0067	0.0047	0.0047	0.0004
Cyclopenta[ed]pyrene	<0.0014[a]	0.0010	0.0014	0.0048	0.0089	0.0051	0.0138	0.0005
Benzo(c)phenanthrene		0.0004	0.0013	0.0016	0.0023	0.0016	0.0046	0.0002
Benz(a)anthracene/chrysene	<0.0014[a]	0.0020	0.0014	0.0125	0.0138	0.0076	0.0371	0.0013
Methyl-benzanthracenes -benzphenanthrenes/-chrysenes	<0.0014[a]	0.0013	0.0016	0.0062	0.0104	0.0062	0.0048	0.0009
C_2-alkyl-benzanthracenes/ -benzophenanthrenes/ -chrysenes		0.0009	0.0014	0.0055	0.0044	0.0037	0.0047	0.0005
Benzofluoranthenes	<0.0014[a]	0.0022	0.0016	0.0128	0.0159	0.0112	0.0141	0.0015
Benzopyrenes/perylene	<0.0014[a]	0.0017	0.0014	0.0083	0.0116	0.0084	0.0094	0.0011
Methyl cholanthrene				0.00007				
Indeno(1,2,3-ed)pyrene								
Benzo(ghi)perylene		0.0013	0.0015	0.0045	0.0099	0.0043	0.0048	0.0011
Anthanthrene								
Dibenzanthracenes/-phenanthrenes		0.0003	0.00005	0.0007	0.0014	0.0010	0.00005	0.0002
Dibenzocarbazoles								
Dibenzopyrenes		0.0007	0.0001	0.0011	0.0010	0.0007	0.00002	0.0005
Total[b]	0.0249	0.0365	0.0360	0.2121	0.3715	0.1885	0.3187	0.0265

Note: Blanks indicate POM compound not detected.

[a] Compound was identified but not quantified because of the detection limits of the analytical method.

[b] The detection limit was taken as the emission factor for compounds that were identified but not quantified.

Wood Stoves

On stove emissions, some tests showed more particulate matter or organic emissions from wet wood while other showed less (17, 19, 21, 22, 23). There seemed to be a slight tendency for wet wood to produce more emissions at the lower burn rates typical of the way most people use their stoves. At higher burn rates, the opposite may be observed. There was also a tendency for pine to produce more particulate matter than oak. It also appeared that smaller sized wood fuel with more surface area may produce less emissions. CO emissions did not show any trend as operating conditions varied. There may be a tendency for lower burn rates to produce more CO but all data do not support this.

Tests have shown that some stove designs tend to emit less particulate matter than others (15, 21, 22). The crossdraft type where the exhaust gases pass through the flame was found to be best of the ones tested. One author (15) was concerned that this type of stove may be the hardest to keep burning or have the smallest operating range.

For control of NO_x emissions, there appeared to be a tendency for lower excess air operation to produce less NO_x. Recall that the "low excess air levels" for stoves are still very high compared to those for conventional combustors. The way the stoves were operated, lower excess air was often associated with a higher burning rate. Thus, there was a slight tendency for NO_x to increase with decreasing load.

There was also a tendency for lower burning rates to produce more hydrocarbons and particulate matter. NO_x as just mentioned, may have behaved the same way. Particulate matter and hydrocarbons also showed a slight tendency to decrease at lower excess air levels.

INDUSTRIAL WOOD COMBUSTION EMISSIONS

Surveyed industrial wood combustion emission data (25-46) were reviewed in detail in the EPA study (3).

Industrial Emissions

Table 4 compares typical emissions from wood-fired industrial boilers, to those from stoker coal-, residual oil-, distillate oil-, and natural gas-fired boilers (3). NO_x emissions from wood-fired boilers are low, significantly less than those from coal, or residual oil firing, and comparable to those from distillate oil or gas firing. Probably the biggest environmental advantage of wood combustion is the negligible SO_2 emissions. CO emissions are somewhat higher than those from conventional fuels. Particulate emissions are significantly lower than those from coal-firing, but higher than those from oil- and [illegible] firing. Perhaps the greatest concern is the apparently high total hydroc[illegible] emissions, and possible associated POM emissions. Nevertheless, POM emissions emission from wood-fired industrial boilers appear to be orders of magnitude lower than those from residential wood systems. Emissions, in general, are also lower for the industrial boilers.

TABLE 4. TYPICAL EMISSIONS FROM INDUSTRIAL BOILERS[a]

Pollutant	Wood g/kg	Wood ng/J	Stoker Coal ng/J	Residual Oil ng/J	Distillate Oil ng/J	Natural Gas ng/J
NO_x	0.8(0.1-1.2)	55(6-97)	210-330	100-200	50-100	30-170
SO_2	0.07(0.01-0.5)	3.5(0.4-23)	500-2400	200-1400	0-200	0
CO	10(0.3-38)	510(14-1,900)	10-150	10-150	10-150	10-150
Particulate	4.2(1.5-13)	240(100-1,300)	1400-2500	20-150	3-15	0-5
Total Hydrocarbon	1.4(0.4-2.1)	100(15-110)	7.5-85	0-25	0-20	0-10
POM		0.1(0.003-20)	0.0006-0.027	0-0.003	--	0
Trace Elements		~50 or less	<29- <260	<2	--	0

[a] Emissions data compiled in reference 3.

Table 5 lists POM emissions measured for several wood-fired boilers and illustrates the broad range in values found (3). Why certain units, notably the first underfeed stoker listed, show much greater POM emissions than other units is not clear.

Effect of Equipment Design and Combustion Conditions

Although the industrial boiler data base is diverse, there appears to be identifiable general ranges for optimal excess air and overfire air levels. Several studies by Junge and Associates (16, 39, 40, 41, 42) on a pilot scale spreader stoker have shown that using excess air levels of 50 to 120 percent, maximizing the overfire air levels, and using greater grate bed depths tend to reduce particulate and probably CO and HC emissions as well. Higher loads tended to increase particulate emissions. Tests in Vermont concluded that excess air levels of 100 to 200 percent were best for smaller sized Dutch ovens and spreader stokers (33). They also found that the location and orientation of the overfire air ports were critical for emissions control. The ports must be far enough above the grates so that the burning bed is not disrupted, but not so high that secondary combustion is not completed.

In one study, spreader stokers were found on the average to give more hydrocarbon emissions (35). This conclusion was based on tests on units operating as-found, with no attempts made to adjust the excess air levels and overfire air levels to minimize emissions.

The smaller sized boilers were found to emit less NO_x on a g/kg basis than the larger sized units (27). Tests on a large sized stoker showed that lower excess air along with overfire air adjustment tended to reduce NO_x (31). Tests on pilot scale units showed contradictory results (29, 30). Lower excess air and reduced load was shown to reduce NO_x in one unit and had no effect in the other units. No effect due to wood moisture was observed.

Bark fuel tends to give more particulate emissions and larger sized particles than wood fired units. Also bark, with more nitrogen content, was found to give higher NO_x emissions.

DISCUSSION

The data base on emissions from residential and industrial-wood-combustion equipment is both limited and diverse. The apparent differences in experimental results are probably due to legitimate but not well defined differences, including: 1) difficulty in quantifying and controlling combustion conditions, 2) variety in designs and sizes of equipment, 3) nonuniformity in properties and condition of wood, and 4) differing firing methods and firing conditions. Nonetheless, it is clear that the major pollutants from the wood combustion are: particulates, hydrocarbons (including organics), and carbon monoxide; bottom-ash streams do not appear to be a problem. Although the important parameters affecting emissions are not well characterized, the major ones appear to be combustion design, firing rate, and excess air level. The area of greatest environmental concern is emissions from residential combustion. On a normalized basis (e.g., kg pollutant/kg wood fired), residential wood-burning units tend to produce significantly

TABLE 5. POM EMISSIONS ($\mu g/m^3$) FROM WOOD-FIRED BOILERS

	Underfeed Stoker	Underfeed Stoker	Dutch Oven	Dutch Oven	Underfeed Stoker	Fluid Bed	Spreader Stoker Low NOx	Spreader Stoker Baseline
Capacity, Mg Steam/hour	0.7	5.6	24.5	41.7	18.5	8.0	91	91
Compound								
Naphthalene	6576	50.9	1253.2	212.5	13.7	461		
Biphenyl	1902		24.5	1.4		38		
Fluorene	1631		7					
Phenanthrene	7819		229.3	7.0	2.1	819	3.2	1.9
Methylphenanthrene	1811						3.4	1.6
Phenylnapththalene	1144							
Fluoranthene	3967		176	2.8	0.1	107	0.8 < 1.3	<.4
Pyrene	4316		107.3	2.1	0.7	84	1.0	<.4
Benzo(a,g,h,i)fluoranthene	1293		15			69	0.7 < 1.2	<.8
Chrysene	919					38	< 0.5	ND
Benzo(a)pyrene	6258		8.4			54	1.2	ND
Benzo(g,h,i)perylene	3510						< 1.2	ND
Indeno(1,2,3-CD)pyrene	719		26				ND	ND
Benzo(6)chrysene	667						ND	<.4
Dibenz(a,i)pyrene	1646						ND	ND
Benzo(c)fluoranthene	384						ND	<.4
Methylbenz(a)anthrecene	598						ND	<.4
Binaphthalene	844							
Coronene	601						2.2	0.1
Anthracene							< 0.4	ND
Methylcholanthrene							< 2.4	<1.9
Total (minimum)	46605	50.9	1847	226	17	1670	12.0 < 18	3.6 < 7.9
Reference	26	45	45	45	45	45	31	31

higher emissions than do industrial boilers, which are more efficient combustion systems. This problem is aggravated by the localized and seasonal concentration of residential wood combustion emissions. Furthermore, residential wood combustion contributes a disproportionately high fraction of the total emissions from the residential sector.

Though the data are limited, emissions on a normalized basis from fireplaces and stoves are roughly comparable, except for CO and the pollutant class of greatest concern, POMs. The slower burn rate, oxygen starved mode of stove operation, which is standard practice for maximum home heating efficiency, is conducive to higher CO and POM emissions, including the potential carcinogen benzo(a)pyrene. Although there is an order of magnitude variation in POM emission rates reported by different investigators, even the low end of that range may be a health hazard.

Increase in residential wood useage is expected to be in expanded stove utilization rather than fireplace because of the former's much higher heating efficiency. Fortunately, stoves appear to have better potential for controlling emissions by combustion modifications, because they have more design and operating parameters, e.g., control of excess air. Certain stove designs, such as cross-draft or downdraft types, which extend flue gas residence times under combustion conditions, may reduce hydrocarbon and particulate emissions. Finally, it should be noted that although NO_x emissions from residential wood combustion are often cited as being low, they are still larger than those from the conventional distillate oil-or natural gas-fired residential systems that wood units often replace.

It is expected that the combustion modification control potential of wood-fired industrial boilers is greater than that of wood-fired residential systems. As noted above, industrial emissions are significantly lower due to better combustion conditions. Comparing industrial wood firing with that of conventional fossil fuels, NO_x and SO_2 emissions are generally considerably lower (with the exception of natural gas combustion which emits no SO_2). The low NO_x and SO_2 emissions from wood firing are significant environmental benefits. Particulate emissions are lower than from coal firing. However, CO and hydrocarbon emissions are significantly higher than from fossil fuels. And it is the possibility of hazardous organic compounds that is of concern.

As with residential data, the effect of wood type and moisture content is not evident from the limited industrial boiler data base. There were no definite emission patterns by boiler design, though larger capacity units tended to produce higher NO_x. For industrial stoker boilers, the dominant design, control of underfire and overfire air offers good potential for reducing particulate, CO, and hydrocarbon emissions.

Finally, it should be noted that POM emissions, though emitted from industrial boilers, appear to be about two orders of magnitude lower than those from residential systems. Nevertheless, the range of reported POM emissions from industrial boilers is quite broad, and experimental testing of field units is needed to help quantify the problem.

CONCLUSIONS

In conclusion, significant data gaps in both residential and industrial wood combustion emissions exist. The most urgent areas needing investigation are the amount and kinds of POM emissions from wood combustors in general, and residential heating units in particular, and the effect of combustion modifications on emissions from both residential and industrial systems. Adaptation of standardized sampling, analysis, and reporting procedures is needed to aid in the comparison of complementary work. An interagency task force on wood combustion, consisting of representatives from EPA, DOE, TVA, Canadian Combustion Research Laboratory, and Environment Canada, is actively examining these issues (47).

REFERENCES

1. Dunwoody, J. E., et al., "Wood Combustion Systems: Status of Environmental Concerns," DOE/EV-0064, U.S. Department of Energy, Office of Technology, Washington, D.C., January 1980.
2. Cooper, J. A., "Environmental Impact of Residential Wood Combustion Emissions and its Implications," J. Air Pollution Control Association, Volume 30, pp. 855-861, 1980.
3. Lips, H. I., and K. J. Lim, "Assessment of Emissions from Residential and Industrial Wood Combustion," Acurex Draft Report FR-81-85/EE, EPA Contract 68-02-3188, Acurex Corporation, Mountain View, CA, April 1981.
4. "Energy from Biological Processes," Congress of the United States, Office of Technology Assessment, Washington, D.C., July 1980.
5. "Annual Report to Congress 1979, Volume Three: Projections," DOE/EIA-0173(79)/3, U.S. Department of Energy, Energy Information Administration, Washington, D.C., 1979.
6. Schweiger, B., "Power from Wood," Power Magazine, Volume 124, pp. S.1-S.32, February, 1980.
7. Hall, E. H., et al., "Comparison of Fossil and Wood Fuels," EPA-600/2-76-056, March 1976.
8. "An Ancient Fuel Provides Energy for Modern Times," Chemical Engineering, Volume 87, pp. 73-76, April 1980.
9. Hall, E. H., et al., "Environmental and Technological Analysis of the Use of Surplus Wood as an Industrial Fuel," EPA-600/7-80-120 (PB-80 209 125), June 1980.
10. "Steam, It Generation and Use," Babcock & Wilcox Co., New York, NY, 1972.
11. Fyling, G. R., ed., "Combustion Engineering," Combustion Engineering, Inc., Windsor, CT, 1966.
12. Schorger, A. W., "Chemistry of Cellulose and Wood," pg. 51, McGraw-Hill, New York, NY, 1926.
13. Cheremisinoff, N. P., "Wood for Energy Production," Ann Arbor Science, Ann Arbor, MI, 1980.
14. Corder, S. E., "Wood and Bark as Fuel," Research Bulletin 14, Oregon State University, Forest Research Laboratory, August 1973.
15. Allen, J. M., "Control of Emissions from Residential Wood Combustion by Combustion Modification," in Proceedings of the Joint Symposium on Stationary Combustion NO_x Control, Volume III, EPA IERL-RTP-1085, October 1980.
16. Tuttle, K. L., "Combustion Mechanisms in Wood Fired Boilers," Ph.D. Thesis, Oregon State University, Corvalis, OR, June 1978.
17. Butcher, S. S., and E. M. Sorenson, "A Study of Wood Stove Particulate Emissions," J. Air Pollution Control Association, Volume 29, pp. 724-728 (1979).
18. Duncan, J. R., et al., "Air Quality Impact Potential From Residential Wood-Burning Stoves," TVA Report 80-7.2, Tennessee Valley Authority, Muscle Shoals, AL, March 1980.
19. DeAngelis, D. G., et al., "Preliminary Characterization of Emissions From Wood-Fired Residential Combustion Equipment," EPA-600/ 7-80-040, March 1980.
20. Haden, A. C. S., and R. W. Braaten, "Performance of Domestic Wood-Fired Appliances," presented at 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 1980.

TYPING GUIDE SHEET

21. Kosel, P., et al., "Emissions From Residential Fireplaces," CARB Report C-80-027, California Air Resources Board, Sacramento, CA, April 1980.
22. Barnett, S. G., and D. Shea, "Effects of Wood Burning Stove Design on Particulate Pollution," Department of Earth Sciences and Department of Chemistry, State University of New York, Plattsburgh, NY, preprint received from Oregon Department of Environmental Quality, Portland, OR, July 1980.
23. Juger, S. J., et al., "Improving the Efficiency, Safety, and Utility of Woodburning Units. Special Creosote Report," DOE Report ORO-5552-T9, U.S. Department of Energy, December 15, 1979.
24. Allen, J. M., and W. M. Cooke, "Control of Emissions from Residential Wood Burning by Combustion Modification," Battelle Draft Report, EPA Contract 68-02-2686, Battelle Columbus Laboratories, Columbus, OH, November 10, 1980.
25. Watson, J. et al., "Source Category Survey for Waste-Fired Boilers," Acurex Final Report 79-S01, EPA Contract 68-02-3064, Acurex Corporation, Morrisville, NC, February 1979.
26. Surprenant, N. F., et al., "Emissions Assessment of Conventional Stationary Combustion Systems: Volume IV. Commercial/Institutional Combustion Sources," Draft Final Report GCA-TR-79-62-G, EPA Contract 68-02-2197, GCA Corporation, Bedford, MA, June 1980.
27. Nunn, A. B., III, "NOx Emission Factors for Wood-Fired Boilers," EPA-600/7-79-219, September 1979.
28. "A Study of Nitrogen Oxides Emissions From Wood Residue Boilers," National Council of the Paper Industry for Air and Stream Improvement Technical Bulletin No. 102, New York, NY, November 1979.
29. Kester, R. A., and M. J. Pilat, "Nitrogen Oxide Emission From a Pilot Plant Spreader-Stoker Bark-Fired Boiler," J. Technical Association of the Pulp and Paper Industry, Volume 63, No. 2, pp. 159-161, 1980.
30. Junge, D. C., "Emissions of Oxides of Nitrogen From Boilers Fired with Wood and Bark Residue Fuels," presented at the Technical Association of the Pulp and Paper Industry 1980 Environmental Conference, Denver, CO, April 1980.
31. Tidona, R. J., and W. A. Carter, "POM Emissions From a Hogged Fuel Spreader Stoker Boiler," KVB Preliminary Report KVB11 6015-1237, EPA Contract 68-02-2645, KVB, Inc., Tustin, CA, May 1980.
32. Hunter, S. C., et al., "Application of Combustion Modifications to Industrial Combustion Equipment," EPA-600/7-79-015a, January 1979.
33. Sanborn, C. R., "Evaluation of Wood-Fired Boilers and Wide-Bodied Cyclones in the State of Vermont," EPA Region I Report, Boston, MA, March 1979.
34. Nunn, A. B., III, "Preliminary Compilation of Data for Emissions From Wood-Fired Boilers," TRW Report, EPA Contract 68-02-2613, Task No. 30, TRW, Inc., Durham, NC, December 1979.
35. Bosserman, P. B., "Hydrocarbon Emissions From Wood Fired Boilers," presented at Air Pollution Control Association Pacific Northwest International Section Annual Meeting, Spokane, WA, November 15, 1977.
36. Bosserman, P. B., "Wood Waste Boiler Emissions in Oregon State," presented at Air Pollution Control Association Pacific Northwest International Section Annual Meeting, Anchorage, AK, September 1976.
37. Boubel, R. W., "Control of Particulate Emissions From Wood-Fired Boilers," EPA 34011-77-026 (NTIS-PB 278 483), 1977.

38. Oglesby, H. S., and R. O. Blosser, "Information on the Sulfur Content of Bark and its Contribution to SO_2 Emissions when Burned as a Fuel," *J. Air Pollution Control Association*, Volume 30, pg. 769, 1980.

39. Junge, D. C., "Investigation of the Rate of Combustion of Wood Residue Fuels," OSU Report RLO-2227-T22-26 for U.S. Department of Energy Contract EY-76-C-06-2227, Task No. 22, Oregon State University, Corvalis, OR, September 1979.

40. Tuttle, K. L., and D. C. Junge, "Combustion Mechanisms in Wood-Fired Boilers," *J. Air Pollution Control Association*, Volume 28, pg. 677, 1978.

41. "Pollution Control in the Forest Products Industry," EPA 625/ 3-79-010, August 1979.

42. Lang, A. J., and D. C. Junge, "Investigation of the Particle Size Distribution and Particle Density Characteristics of Douglas Fir Hogged Fuel Fly Ash Collected Under Known Combustion Conditions," Oregon State University Report RLO-2227-T22-6 for Department of Energy Contract EY-76-C-06-2227, Task No. 22, Oregon State University, Corvalis, OR, December 1978.

43. Szabo, M, *et al.*, "Control of Salt-Laden Particulate Emissions from Hogged Fuel Boiler," Report for EPA Region X Contract 68-01-4147, Task 51, Seattle, WA, May 1979.

44. Adams, T. N., "Predictions of Intrinsic Ash Emissions from Wood-Waste Boilers," J. Air Pollution Control Association, Volume 30, pg. 147, 1980.

45. Surprenant, N. F., *et al.*, "Emissions Assessment of Conventional Stationary Combustion Systems: Volume V: Industrial Combustion Sources," Draft Final Report GCA-TR-79-62-G, EPA Contract 68-02-2197, GCA Corporation, Bedford, MA, October 1980.

46. Waterland, L. R., *et al.*, "Environmental Assessment of Stationary Source NOx Control Technologies -- Final Report," Acurex Draft Final Report FR-80-57/EE, EPA Contract 68-02-2160, Acurex Corporation, Mountain View, CA, April 1980.

47. Hall, R. E., Personal Communication, U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, NC, March 1981.

TYPING GUIDE SHEET

AMBIENT AIR ASSESSMENT IN A RURAL NEW ENGLAND VILLAGE WHERE WOOD IS THE DOMINANT FUEL

by: James F. Hornig, Roger H. Soderberg, and Deborah Larsen
Department of Chemistry
Dartmouth College
Hanover, NH 03755

Carlo Parravano
Department of Chemistry
State University of New York
College at Purchase
Purchase, NY 10577

ABSTRACT

During the 1979-80 heating season, fifty standard hi-vol filter samples of ambient air were taken in a small town and in semi-rural areas in New Hampshire where wood is the dominant heating fuel. In addition to total suspended particulate (TSP) values, concentrations of 12 polycyclic organic materials (POM), 10 of which are priority pollutants, were determined using HPLC with UV and fluorescence detection, and by GC/MS techniques. Concentrations of benzo(a)pyrene were found to be in the range 0.5-0.8 ng/m^3. Our measurements will be compared to recently published POM values from diverse sources. This comparison will include discussion of troublesome methodological problems which potentially compromise ambient air POM analyses.

INTRODUCTION

Contamination of ambient air by carcinogenic polycyclic aromatic material (POM) from a variety of low-temperature combustion sources is a matter of serious concern. Between 1965 and 1975 the nationwide average benzo(a)pyrene concentration in ambient air decreased, probably because of a decrease in low-temperature coal combustion and the increasing control of coke-oven emissions and open burning during that period (Figure 1).*

---

* R. B. Faoro, J. A. Manning, J.A.P.C.A., 31, 62 (1981)

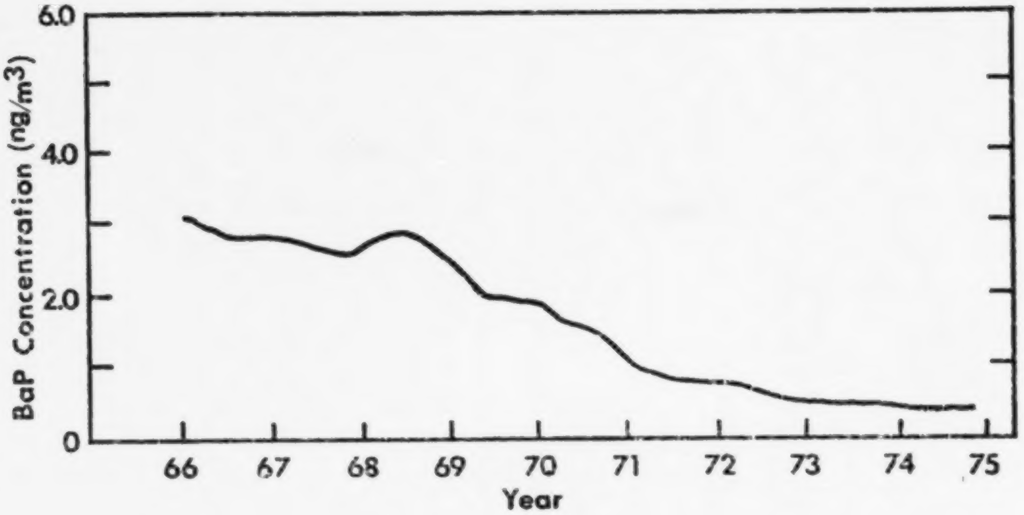


Figure 1. Historical trend of benzo(a)pyrene concentration: a composite average of 34 urban NASN sites

Since 1973, however, there has been a dramatic increase in the use of wood for home heating. The contribution of home wood combustion to the total burden of air pollutants has increased to the point where some communities, especially in closely settled neighborhoods in inversion prone valleys, have considered imposing restrictions on the use of woodstoves and fireplaces. A recent study by Monsanto Research* estimates that residential woodstoves contribute 80% of the total burden of polycyclic organic material (POM) originating from stationary sources.

Although there has been extensive monitoring of various POM concentrations in ambient air at many locations, and although there have been several recent studies of emission factors from woodstoves and fireplaces, there are no ambient air studies in which the observed POM could be attributed directly to woodsmoke. This paper presents preliminary results of such a study.

We have collected samples of ambient air particulates using a standard high-volume sampler in Lyme Center (pop. ≃300), a rural New Hampshire village free of industry and remote from a major highway. A house by house survey in 1979-80 indicated that over 60% of the homes were heated at least in part with wood, and wood heat is even more important now. There is usually very little automobile traffic through the village itself except on good skiing days when it hosts traffic to a local ski hill.

---

* D. G. DeAngelis, D. S. Ruffin, J. A. Peters, R. B. Reznik, "Source Assessment: Residential Combustion of Wood," EPA-600/2-80-042b.

Three other sites were used for comparison: a residential area of Hanover, NH, (pop. 6,000) and two sparsely settled rural sites (Moose Mountain and Brigham Hill) located several miles east and west of Hanover on either side of the Connecticut River Valley, approximately 1400 feet and 800 feet above the river, respectively, and close to several occupied residences. Woodstoves are common in Hanover, but most residential heating is with oil and there are two large oil-fired central heating installations at Dartmouth College and Mary Hitchcock Memorial Hospital. In addition, there is a substantial amount of automobile traffic in Hanover.

EXPERIMENTAL

During this first year of the study all filters were Gelman glass fiber filters. Samples were usually collected for 48 hours at a sampling rate of about 80 m^3 per hour. Filters were either extracted immediately, or folded, wrapped in aluminum foil and stored at -10°C. For extraction, the filter was cut into 1 cm^2 pieces and bathed for 12 hours in a Soxhlet extractor using a toluene-ethanol mixture and a pre-extracted thimble. The sample preparation procedure is shown in Figure 2. Samples are protected from direct light and stored in a refrigerator whenever possible.

Analysis was carried out primarily by HPLC, using a Perkin-Elmer reverse phase PAH-10 C_{18}-ODS column especially selected for PAH analysis. A solvent program beginning with 15 minute at 50-50 acetonitrile-water, followed by an 8 minute linear gradient to 100% acetonitrile and then 27 minute isocratic flow at 100% acetonitrile separated the compounds adequately. Eluting compounds were detected by a UV detector set at 254 nm in series with a fluorescence detector (excitation 305 nm, detection 430 nm). The use of the fluorescence detector provided increased sensitivity for many of the POMs, and the ratio of UV to fluorescence signals for each compound provided supplementary information for peak identification. Primary peak identification was provided by comparison of retention times with known samples, and also by direct spiking of unknowns with known samples. Quantitation was achieved by adding an internal standard 3,3'-diphenylbiphenyl to the sample and using relative response factors obtained by similar spiking of a standard sample. Such spiked standards were run every morning as a continuing check on column performance.

A parallel effort with GC/MS was used to identify and quantitative PAH components in some samples. The mass spectrometer is a Finnigan model 4000 with a fused silica capillary column coated with SE-52.

RESULTS AND DISCUSSION

Numerical results are given in Table 1, with illustrative groupings of data presented in Figures 3, 4, 5 and 6. The results in Table 1 are averaged over all filters collected at each site in order to give a representative average of the TSP and POM burden encountered at each site. The averaged POM values are also useful for giving the best picture of the relative amounts of each POM--a pattern which we have termed the "fingerprint" of the site.

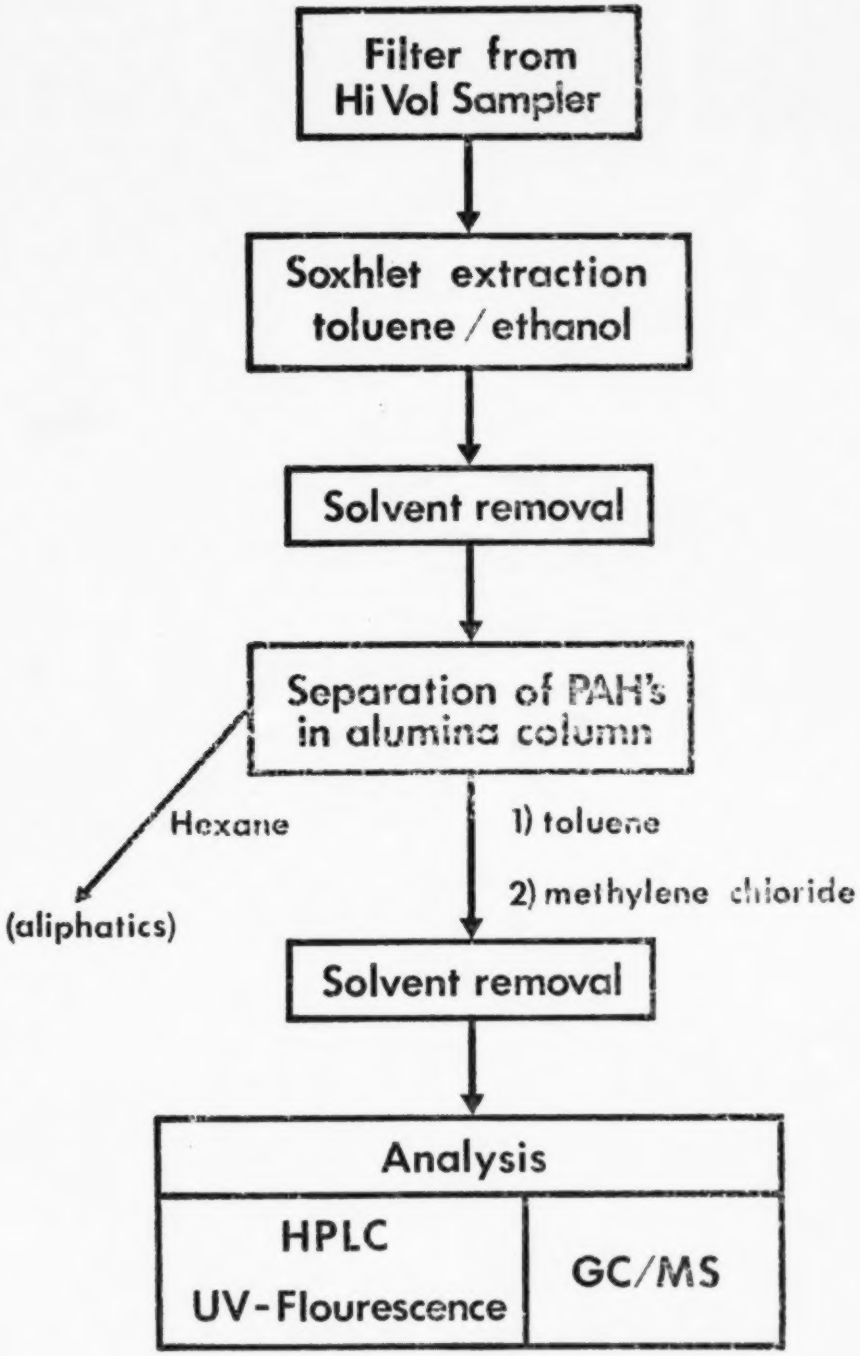

Filter from Hi Vol Sampler
Soxhlet extraction toluene / ethanol
Solvent removal
Separation of PAH's in alumina column
Hexane
(aliphatics)
1) toluene
2) methylene chloride
Solvent removal
Analysis
HPLC
UV-Flourescence
GC/MS

Figure 2. Flow diagram for sample extraction and analysis

4

TABLE 1. POM CONCENTRATIONS AT INDICATED LOCATIONS (ng/m^3)

Substance	Lyme Center Average	Urban Hanover Average	Moose Mountain New Hampshire Average	Brigham Hill Vermont Average	Worst Case Lyme Center
Phenanthrene	.01	.63	.18	.12	0
Anthracene	.02	.08	.02	.03	.04
Fluoranthene	.44	2.59	.41	.40	2.61
Pyrene	.49	3.05	.43	.52	2.70
Triphenylene	.04	.52	.17	.15	0
Benz(a)anthracene	.41	1.29	.33	.32	1.43
Chrysene	.63	1.77	.61	.44	2.07
Benzo(e)pyrene	.93	2.55	.87	.74	2.18
Benzo(b)fluoranthene	.83	1.88	.88	.54	2.91
Benzo(a)pyrene	.54	1.52	.37	.50	1.23
Dibenz(a,h)anthracene	1.92	4.79	1.71	1.33	6.71
Benzo(ghi)perylene	.65	1.81	.55	.47	2.06

Figure 3 shows the TSP values for each of the filters collected at the Lyme Center site. They vary by a factor of 5 and have an average of 52 $\mu g/m^3$. The highest value (100 $\mu g/m^3$) was associated with a clear, cold, windless episode with a marked inversion. This filter also gave the highest POM values, though in general the POM concentrations showed only weak correlation with TSP values. We attribute this lack of correlation to the fact that the winter of 1980 was virtually snowless in the Northeast, so that the windborn dust would be expected to contribute substantially to TSP values. Figure 4 shows TSP values for the four sampling sites averaged by month. The two "rural" sites are generally somewhat lower than the two village sites, as might be expected.

Figure 5 shows, at the bottom, the averaged Lyme Center "fingerprint." The top two boxes show comparable data for Moose Mountain, a rural hilltop site east of Hanover, and for Brigham Hill, the comparable rural site west of Hanover. It is notable that the fingerprint patterns of all three sites are virtually identical. Given the extensive woodburning in Lyme Center and the fact that all filters have a distinctive woodsmoke smell, it is tempting to identify this fingerprint, at least tentatively, with woodsmoke. This conclusion is consistent with Hites's* observation that benz(a)anthracene and chrysene are prominent products of wood combustion but not of kerosene, which Hites uses as a model compound for fuel oil combustion. Substantial amounts of these two compounds are evident in Figure 5.

The other principle feature of Figure 5--the virtually identical magnitude of the average POM concentrations at the three sites--is surprising. This observation suggests that on most days large scale mixing of air, extending at least over the entire Connecticut River Valley area, dominates the Lyme Center environment. Extensive additional observations would have to be made to determine whether this reflected some fortuitous location of the hi-vol sampler, or an absence of appropriate inversion conditions during our testing periods. These possibilities are being examined during the 1981 testing program. A summertime blank at the Lyme Center site shows virtually no detectable POMs.

Figure 6 compares the same averaged Lyme Center "fingerprint" to the "worst case" sample collected in Lyme Center, and to the averaged urban Hanover results. The worst case sample shows that under appropriate conditions the local POM concentration can increase by a factor of more than five. Taking benzo(a)pyrene as an index, the observed high value of 1.2 ng/m^3 approaches typical urban values, though it is still well below the values associated with areas near heavy coal using facilities (see Table 2).

The results from urban Hanover suggest two conclusions. First, the overall POM burden in Hanover is comparable to the worst case in Lyme Center, and second, the fingerprint pattern of Hanover is not appreciably different from that of Lyme Center. The Hanover site was in a residential area of the

---

* M. L. Lee, G. P. Prado, J. B. Howard, Ronald A. Hites, Biomed. Mass. Spect., 4, 182 (1977).

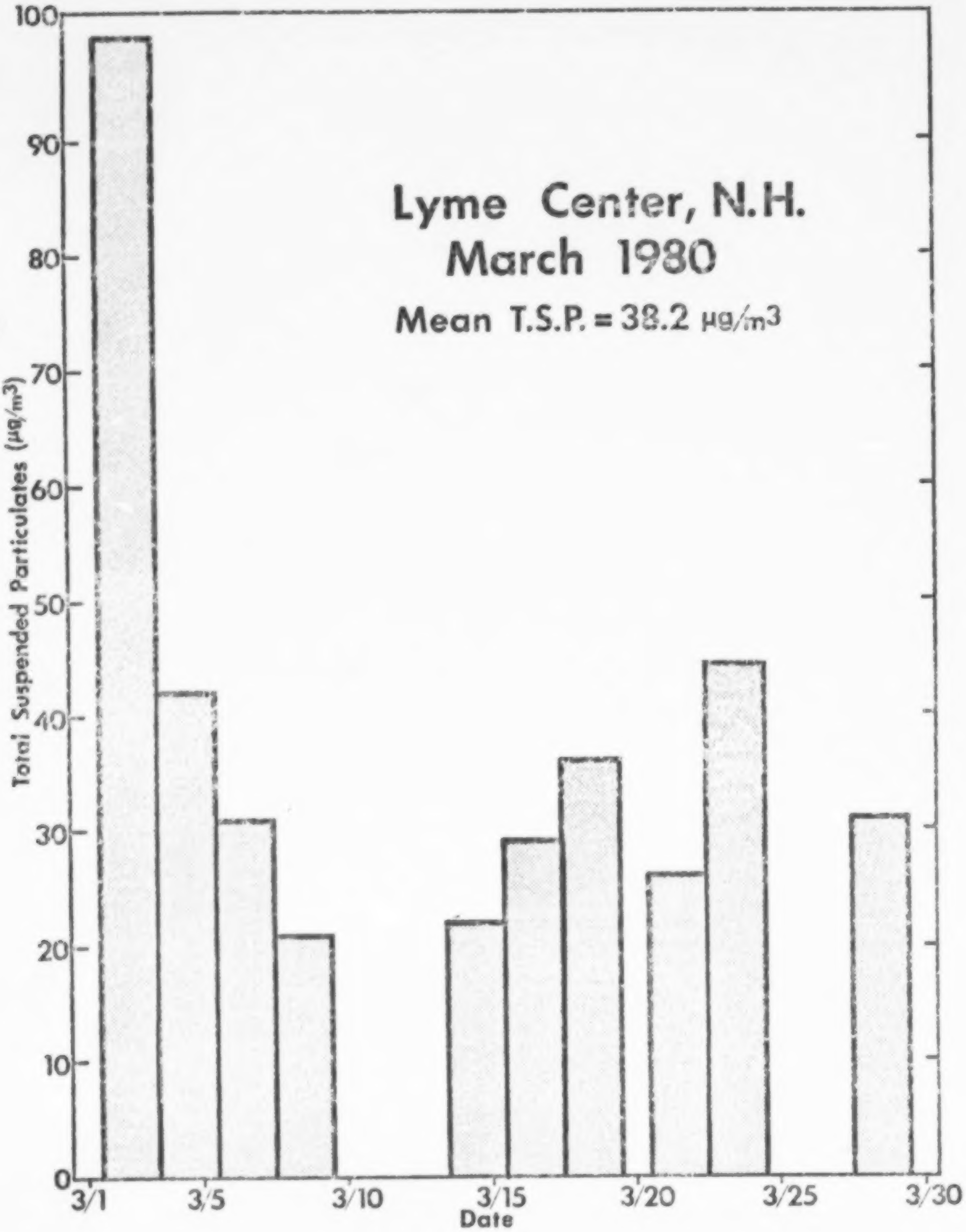


Figure 3. Total suspended particulates (TSP) on 48 hour high-volume filter samples collected in Lyme Center, NH, during March 1980

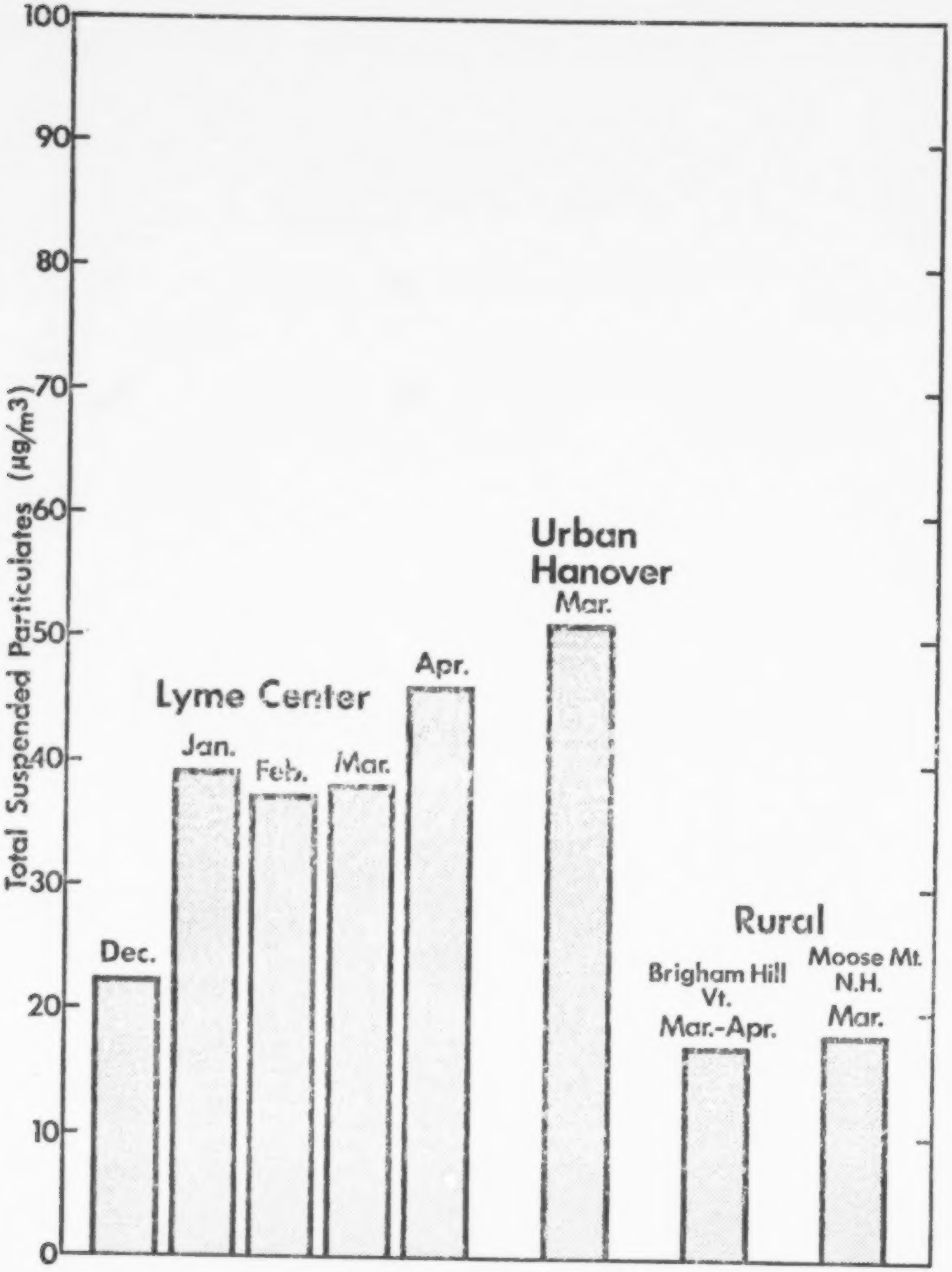


Figure 4. Monthly average of total suspended particulates (TSP) collected during 48 hour periods at indicated sites

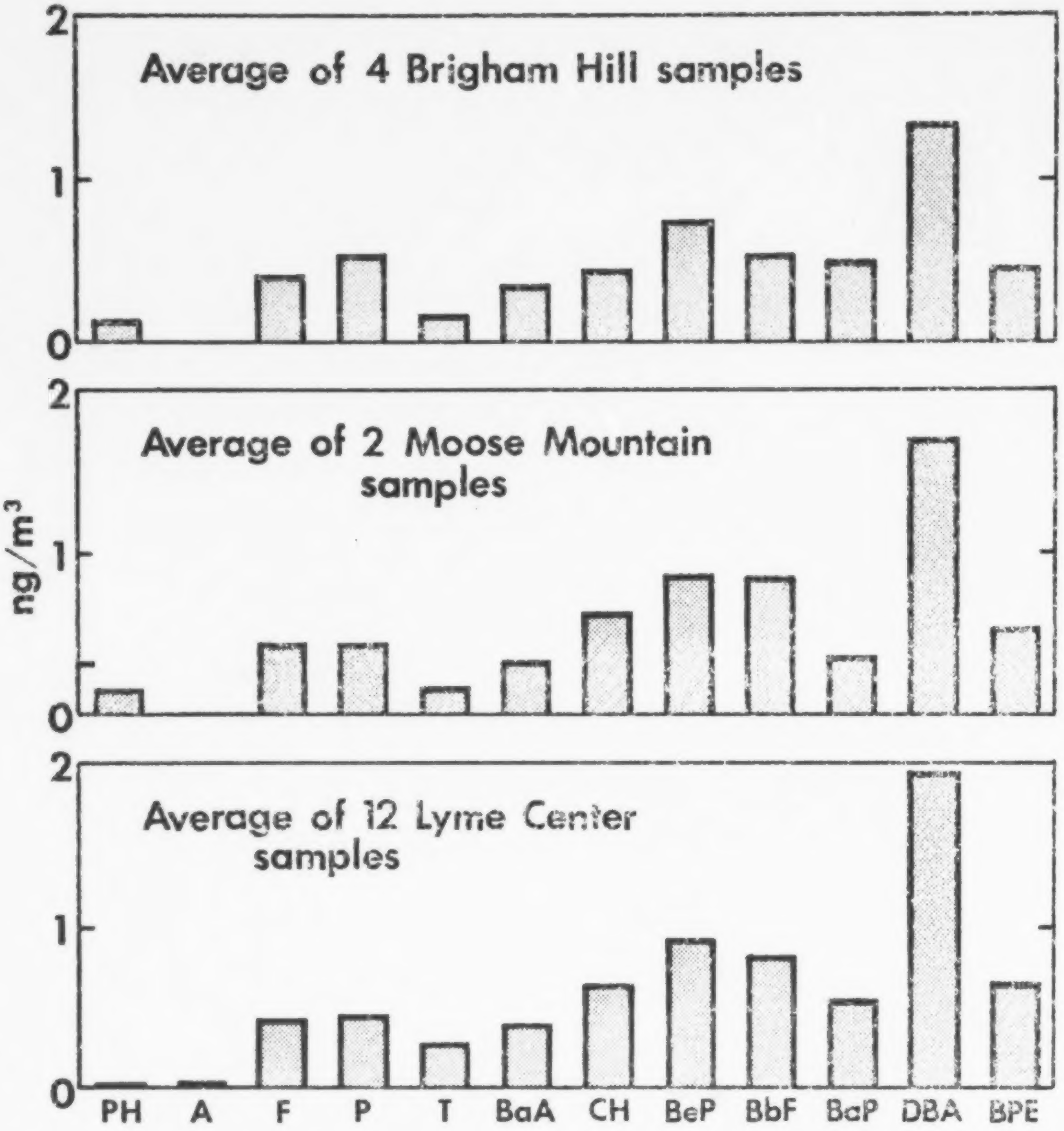


Figure 5. Comparison of average Lyme Center "fingerprint" with rural samples from Moose Mountain, NH, and Brigham Hill, VT.

PH=phenanthrene, A=anthracene, F=fluoranthene, P=pyrene, T=triphenylene, BaA=benz(a)anthracene, CH=chrysene, BeP=benzo(e)pyrene, BbF=benzo(b)fluoranthene, BaP=benzo(a)pyrene DBA=dibenzo(ah)anthracene, BPE=benzo(ghi)perylene

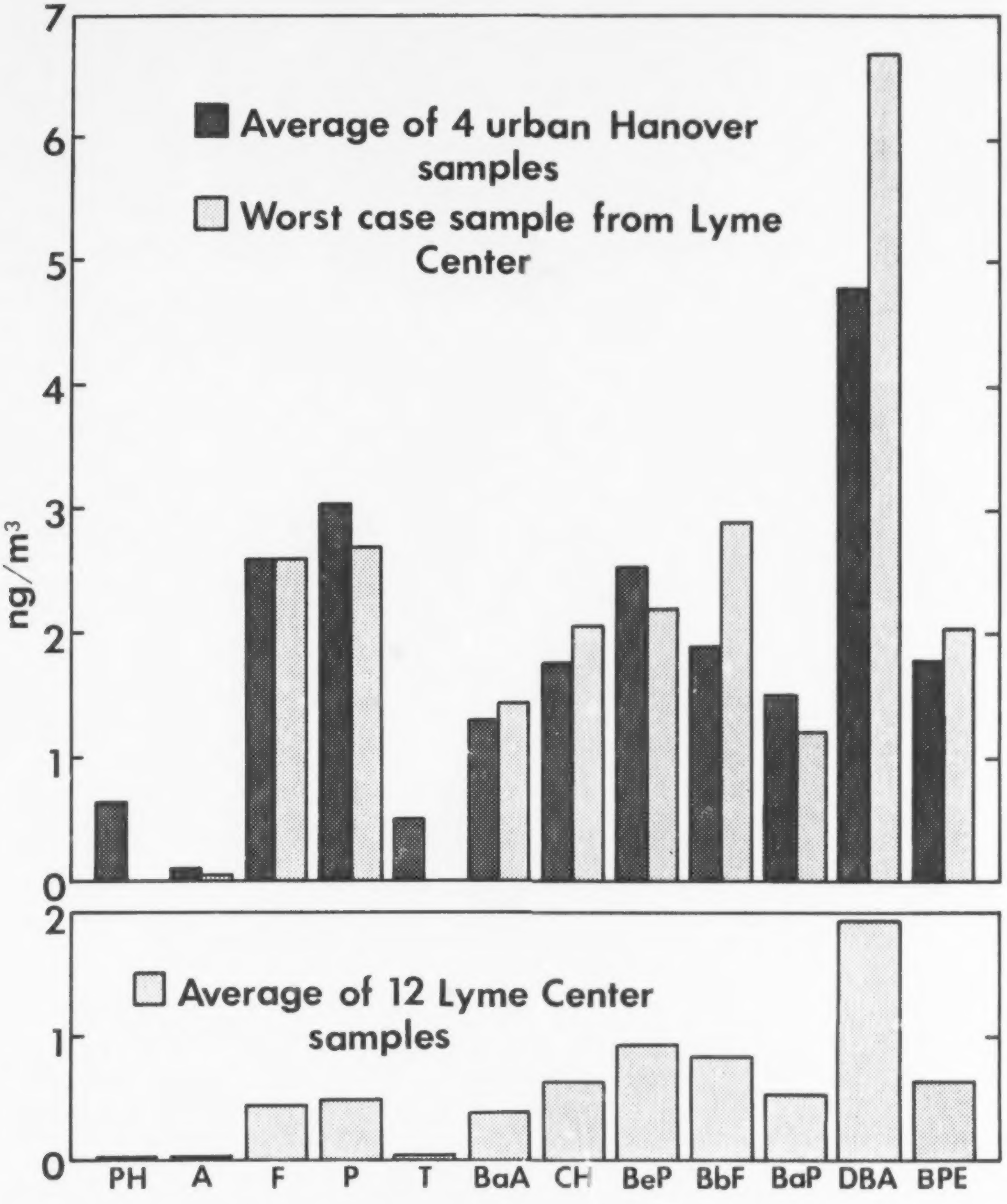


Figure 6. Comparison of the average Lyme Center "fingerprint" with the worst case Lyme Center sample and with the average urban Hanover results.

PH=phenanthrene, A=anthracene, F=fluoranthene, P=pyrene T=triphenylene, BaA=benz(a)anthracene, CH=chrysene, BeP=benzo(e)pyrene, BbF=benzo(b)fluoranthene, BaP=benzo(a)pyrene DBA=dibenzo(ah)anthracene, BPE=benzo(ghi)perylene

TABLE 2. AMBIENT BaP CONCENTRATIONS IN VARIOUS LOCATIONS

Location	BaP Concentration (ng/m^3)	Conditions	Reference
New York City, NY	0.3-3.5	Aug. 1976	1
Pasadena, CA	0.39-1.06	Oct. 1976-Mar. 1977	2
Karlsruhe, Germany	0.2-42.5	Oct. 1975-Mar. 1976	3
New York City, NY	1.15-1.30	Annual average, 1975	4
Claremont, CA	.17-1.16	Spring 1979	5
Toronto, Canada	0.1-0.8	Two summer and two winter months 1974	6
Essen, Germany	6-60	Residential coal heating area	7
	1.3-66	Oil heating area	
	2-100	Auto tunnel	
	11-208	Vicinity of coke ovens	
	0.5-8	Rural location	
Lake Michigan	0.3-1.8	Spring, summer, fall June 1975-Aug. 1977	8
Hamilton, Ontario	2.30-3.62	Annual average for 1975/76 and 1977/78	9
Los Angeles, CA	0.46	Annual average, 1974/75	10
Chicago, IL	1.0	Annual average, 1975	11
New York City, NY	0.9	Annual average, 1975	11
Pittsburgh, PA	2.1	Annual average, 1975	11
Tucson, AZ	0.4	Annual average, 1970	11
Ashland, KY	4.7	Annual average, 1975	11
Anchorage, AK	0.8	Annual average, 1970	11
Denver, CO	2.2	Annual average, 1970	11
Duluth, MN	1.1	Annual average, 1970	11
Altoona, PA	19.3	Annual average, 1970	11
Youngstown, OH	7.1	Annual average, 1970	11
Coos County, NH	0.1	Annual average, 1970	11

TABLE 2 (continued)

References

1. J. Daisey, M. Leyko, T. Kneip, in Polynuclear Aromatic Hydrocarbons, edited by P. Jones and P. Leber, p. 201, Ann Arbor Science, Ann Arbor, Michigan (1979).
2. A. Miguel, ibid., p. 383.
3. H. Gusten, G. Heinrich, ibid., p. 357.
4. M. Dong, D. Locke, E. Ferrand, Anal. Chem., 48, 368 (1976).
5. J. N. Pitts, "Geographical and Temporal Distribution of Atmospheric Mutagens in California," Final Report, California Air Resources Board, Contract Number A7-138-30, May, 1980, p. 49.
6. R. Pierce, M. Katz, Environ. Sci. Technol., 9, 347 (1975).
7. G. Grimmer, K.-W. Naujack, D. Schneider, in Polynuclear Aromatic Hydrocarbons, edited by A. Bjørseth, A. Dennis, p. 197, Battelle Press, Columbus, Ohio (1980).
8. J. Strand, A. Andren, ibid., p. 127.
9. M. Katz and C. Chan, Environ. Sci. Technol., 14, 383 (1980).
10. R. Gordon, Environ. Sci. Technol., 10, 370 (1976).
11. USEPA, Health Assessment Document For Polycyclic Organic Matter, May, 1978, USEPA, Office of Research and Development, Washington, DC, pp. 5-5 to 5-18.

city where the housing density is appreciably greater than that of Lyme Center (180 houses within a one half mile radius vs. 80 houses within a one mile radius in Lyme Center). Many of the Hanover houses use woodstoves as auxiliary heat sources though few are heated exclusively with wood. Thus it appears that the specific Hanover site we selected has average POM concentrations which are considerably higher than the background average in the river valley.

The absence of marked changes in the Hanover fingerprint which might reflect the dominant fuel oil use in Hanover cannot be explained with present information. Either the local environment of our test site is dominated by nearby woodstoves, or the fuel oil fingerprint is not sufficiently different to be detected by our present analyses. The fact that a single summer sample showed POM concentrations similar to the Lyme Center average except for an anomalously high pyrene concentration does not resolve the issue. Additional sampling sites and more extensive analytical procedures using GC/MS techniques are being used during the current testing series to help answer these questions.

During the course of our project we have become increasingly concerned with several methodological problems which potentially compromise much current ambient air POM analysis. There have been persistent literature reports of substantial errors caused by incomplete collection of POM bearing particulates, incomplete extraction of POMs from particulate material, and chemical degradation of POMs during the collection and analysis.

There have been reports,* for example, that more than 50% of some POMs may be on particles too small to be collected on glass fiber filters. Other studies** have suggested that recovery of POMs from some particulates is exceedingly difficult, with recoveries in some cases being well below 50%. Finally,*** there have been several studies of chemical and photochemical degradation of POMs on the filter and during various steps of the analysis. There are, to be sure, other literature reports which give assurance that no difficulties exist in any of these areas, but in an area as vital as ambient air POM analysis we believe that substantial work directed towards unambiguous verification of methods is needed.

In our own work, as interim measures, we are switching to Teflon coated filters (Pallflex TXOHI20-WW), which minimize degradation on the filter. We also extract samples by sonification instead of Soxhlet extraction in order to reduce the time and severity of that step. We have adopted a solvent extraction technique**** to clean up the samples before analysis by HPLC or GC/MS. This involves initial extraction of the organic material with cyclohexane followed by a solvent-solvent partition of dimethylformamide and water to isolate and concentrate the PAHs. We also handle all samples in a room equipped with yellow fluorescent light (450 nm cutoff) to minimize chances of photo oxidation.

---

* A. M. Krstulovic, D. M. Rosie, P. R. Brown, Amer. Lab., p. 11 (1977).

** P. W. Jones in Polynuclear Aromatic Hydrocarbons edited by A. Bjorseth, A. J. Dennis, pp. 1085ff, Batelle Press, Columbus, OH (1980).

*** F. S.-C. Lee, W. R. Pierson, J. Ezike, ibid., p. 543.

**** C. Peter Flessel, et. al., "The Integration of the Ames Bioassay and Chemical Analysis in an Epidemiological Cancer Incidence Study," Report No. CA/DO/AIHL/R-216, Air and Industrial Hygiene Laboratory, Calif. Department of Health Services, Berkeley, CA.

CONCLUSIONS

Concentrations of POMs were determined in ambient air samples in the small community of Lyme Center, NH, where wood was the dominant heating source. Although occasional atmospheric conditions led to POM concentrations comparable to those reported in large urban areas (BaP $\simeq 1$ ng/m^3), the ambient air quality most commonly reflected the lower POM values associated with the surrounding rural area. By contrast, POM measurements in the larger town of Hanover, NH, regularly approached the typical urban values. The Hanover samples were also surprising in that the fingerprint given by relative concentrations of various POMs did not differ appreciably from the Lyme Center pattern, despite the fact that oil is the dominant domestic and commercial heating fuel in Hanover. Finally, we feel the need for additional research to verify the absolute reliability of POM determinations made by standard literature procedures, including our own. We do not feel that persistent reports of inefficient filtration, incomplete extraction, and chemical degradation have been examined adequately enough to guarantee that these very important data are not subject to large absolute errors.

An Integrated Environmental Assessment of Biomass Energy Development in the Tennessee Valley

by: Paul Schwengels
Office of Research and Development (RD-681)
U.S. Environmental Protection Agency
Washington, D.C. 20460

Charles Bohac
Office of Natural Resources
Tennessee Valley Authority
Chattanooga, TN 37401

Kit Krickenberger
The MITRE Corporation
McLean, VA 22102

Abstract: In recent years, rising prices and availability problems associated with other fuels have generated a great deal of interest in biomass, and particularly wood, as an energy source. At the same time, concerns have been raised about the possibility of negative effects on the environment and on public health and safety which might result from extensive use of this energy source. This paper describes a study currently in progress which attempts to pull together the available information on the potential for biomass utilization in the Tennessee Valley Authority (TVA) region and the possible environmental and health hazards associated with this development. The study will also evaluate a range of public policy options which might be implemented at various levels of government to promote environmentally sound development of biomass energy resources. The paper describes the study approach used and presents preliminary findings. Expected results at the completion of the study are also identified.

INTRODUCTION

Since the Arab oil embargo and resultant quadrupling of world oil prices in the winter of 1973-74, the American public and government have became increasingly aware of the rising cost of energy for all applications. One particularly painful aspect has been the rapid increase in cost of fuels for residential space heating. In response to this situation many homeowners have returned to a traditional renewable energy source - wood combustion. In addition, some industries are beginning to shift to wood as a source of process and space heat. Finally, numerous government organizations at several levels have begun to implement policies to promote

TYPING GUIDE SHEET

the rapid development of wood and other biomass for energy recognizing a locally available renewable alternative to increasingly expensive fossil fuels and electricity.

Biomass is defined as living or recently living material which can be converted to energy. This of course encompasses wood, but also includes agricultural products and municipal and animal wastes.[1] Biomass, like other renewable energy sources, has generally been viewed as environmentally benign, particularly when compared to some fossil fuel alternatives. Increasing concerns are developing, however, about the effects which rapid biomass energy development could have on the environment, public health, local economies, etc.

Biomass development is currently occurring in several areas of the country. One region which has already experienced a substantial growth in the use of biomass energy, and particularly wood, is the Tennessee Valley. Similar developments have been observed in New England, other parts of the Southeast, some Midwestern states, the Rocky Mountain region and the Northwest. It appears likely that some types of biomass development will continue to expand in the Tennessee Valley region with or without government encouragement. Others are currently being considered for promotion through demonstration projects, incentives, etc. It is important that the potential effects of such developments and of alternative strategies for promoting biomass be evaluated comprehensively.

Accordingly, the Environmental Protection Agency (EPA) and the Tennessee Valley Authority (TVA) are jointly supporting a study which analyzes a wide range of potential effects of biomass development in the TVA service region and evaluates policies available to many levels of government and private industry to promote environmentally sound development. This paper discusses the Integrated Assessment approach to policy evaluation (which has been developed by EPA over the past several years), the specific application of that approach to the problems of biomass energy development in the Tennessee Valley region, preliminary results of that application and expectations for the remainder of the study.

INTEGRATED ASSESSMENT

In the early 1970s, a great deal of effort was expended in reviewing the ongoing federal research on environmental effects of energy development and identifying outstanding research needs.[2] These efforts culminated in the establishment of the Federal Interagency Energy/Environment Research and Development Program, one component of which is Integrated Assessment. This component was intended to identify "environmentally, socially and economically acceptable

EPA-287 (Cin.)
(4-76)

(energy development) alternatives".[3] This analysis was to be achieved by integrating results of other research areas, particularly socioeconomic research and health and ecological effects, and by supplementing these results with cost/benefit/risk analyses and comprehensive evaluation of the impacts of alternative polices.[4]

In carrying out this responsibility, the program attempts to achieve several objectives. First, integrated assessment ties together results of scientific and engineering research programs and presents these results in a format that is relevant to policy and regulatory strategy issues. This includes feedback to the research programs concerning information needs of policy makers not being met by these programs. In addition, Integrated Assessment combines with technical research results the socioeconomic, institutional, and policy analysis methods necessary to identify a full range of energy/environmental policy options and to evaluate their probable implications. Finally, the program attempts to identify and evaluate second and higher order impacts of development, including synergistic and cumulative effects of combinations of facilities or technologies.

Integrated Assessment studies are an adaptation of a type of long range policy analysis referred to as "technology assessment (TA)" or "social assessment of technology (SAT)."[5] Joseph Coates has defined TA as "a class of policy studies which attempts to look at the widest possible scope of impacts on society of the introduction of a new technology or the extension of an established technology in new and different ways. Its goal is to inform the policy process by putting before the decision-makers an analyzed set of options, alternatives and consequences."[6]

In the past decade this interdisciplinary approach to policy analysis has received a great deal of attention in the United States through the National Science Foundation (NSF), and other governmental and private organizations.[7] In addition, the concept has received attention within other countries and some international organizations such as the Organization for Economic Cooperation and Development (OECD).[8]

The Integrated Assessment Program has applied this approach to two specific types of problems. One is the evaluation of a specific category of energy technologies (e.g. generation of electricity) on a national level.[9] The other type is the analysis of energy development in a specified region of the country. To date two major regional integrated assessments have been completed. One of these focused on eight resource rich western states and the other evaluated the concentration of power plants and associated coal development in the Ohio River Basin.[10]

The mechanics of the regional integrated assessment process as applied by EPA in the past several years can be separated into four sets of activities. These are description, scenario development, impact assessment and policy analysis. Description includes the establishment of boundary conditions for the study - geographic region, energy technologies of concern, and time period. Baseline conditions in the study region are also described including existing economic, population, and environmental status. In addition attention must be given to identifying current and potential interested parties or "stakeholders" associated with regional energy development and the institutional and policy systems within which this development takes place. A final descriptive element is the characterization of the energy technologies of concern including both currently commercial technologies and more advanced technologies which might be expected to make an impact during the study period. The characterization might include engineering design information, capital and operating costs, and pollutants released to the air, land and water.

The scenario development component involves the construction of a range of logical, internally consistent alternative patterns of energy activity which could occur over the study period. The scenarios can include both specification of the distribution of energy facilities throughout the region and more detailed site specific projections for case study analysis. A scenario approach serves two major purposes. First it allows the consideration of the sensitivity of impacts of energy development to alternative assumptions about the future state of the economy, society, world energy prices, etc., which cannot be anticipated with any accuracy. In addition, alternative senarios can contain broadly differing assumptions about regional energy policy allowing the comparison of the long-range consequences of these broad alternatives. It is important to realize that scenarios are projections, not predictions. They are a framework for thinking about future consequences of technology development and policy decisions but do not necessarily imply actual future occurances.[11]

Impact analysis is the attempt to identify and evaluate the full range of environmental, economic, social, institutional and public health impacts associated with energy development under alternative scenarios. Special attention is given to identification of effects which are indirect, long-term, counter-intuitive or otherwise not immediately evident. Integrated assessments have used an assortment of computer models as well as other analytic techniques to assist the research team in this process.[12] An additional complexity which affects the entire integrated assessment process is especially evident here. This is the need to deal with uncertainty in available scientific knowledge. Clearly, it is not possible to accurately estimate all impacts of future applications of energy technology. Researchers must explicitly deal with the level of uncertainty in all such quantitative findings.

The fourth component of integrated assessment is policy analysis. Whenever adverse effects of energy development are identified in impact analysis, the study team identifies and evaluates alternative policies which could be implemented to avoid or mitigate these effects. The evaluation of alternative policies includes careful consideration of the indirect and long-term consequences of each policy. The four components described are not sequential steps but overlapping activities. Ideally, researchers would complete several iterations of the entire process, varying policy assumptions to identify their full consequences. In practical terms, the ability to do this is always constrained by limitations of funding and time.

There are additional considerations which add to the complexity and difficulty of the already complex process described above. First is the use of an interdisciplinary research team. The continued interaction of a team of experienced, knowledgeable and creative individuals representing a number of specialized disciplines is critical to the success of such a study. There are great difficulties inherent in managing such an interdisciplinary effort, but it is one of the key elements of integrated assessment.[13]

A second consideration is the involvement throughout the study of the major interested parties. This could include representatives of various federal, state, regional and local government organizations, environmental and public interest groups, private industry, trade associations, labor, agriculture and academia. This involvement insures that all issues of importance to these groups are addressed by the study. In addition it may provide some of the technical information needed for analysis and certainly provides an ongoing critique of the comprehensiveness and credibility of the analysis. It can also contribute to the development of consensus among the various interest groups, which is an important element of the political feasibility of the technicially available options.

The final consideration is an ongoing relationship with the policy process. It is useful to identify policy-making bodies and individuals at all levels and to the maximum degree possible involve them during the study. This tends to inject political realities into what could otherwise become an academic exercise. It also can build credibility for the study results and can assist the researchers in presenting results in a format which is useful to policy-makers.

THE NEED FOR A BIOMASS ASSESSMENT

In response to the changing energy situation, the Tennessee Valley Authority (TVA) over the past several years has taken policy actions to promote the utilization of renewable biomass energy sources to replace existing use of natural gas, oil and electricity within the region. TVA also announced the intention of developing an ongoing biomass program which would promote this shift over a period of years. The exact nature of this program is still being determined, but it currently includes wood combustion in residences and industry, more advanced technologies for converting wood to energy (e.g. pyrolysis) and alcohol fuels development.[14] In addition, it has become apparent that biomass development in some areas will continue to increase without government incentives. Residential wood heating, wood combustion in some industrial applications and some alcohol fuel developments appear to fall into this category.

There are, however, a number of environmental, health and safety concerns associated with biomass energy, which warrant further examination. In assessing alternative plans and policy strategies for encouraging the use of biomass, TVA has recognized that potential impacts associated with this use cover all media and should be evaluated carefully. Also, the success of all biomass-for-energy programs ultimately depends on the preservation and renewal of the biomass resources from which the energy is derived. Because of these considerations, TVA, proposed the Biomass Integrated Environmental Assessment (BIEA) Project.

The TVA's goals for this assessment are: (1) to provide an early warning of possible adverse environmental and socioeconomic consequences which may arise from the accelerated use of biomass for energy in the TVA area; (2) to identify strategies for mitigating adverse consequences; (3) to provide a means of evaluating alternative program strategies before implementation; and (4) to demonstrate integrated assessment methodologies within TVA.

The a study is also consistent with the goals of the EPA Integrated Assessment Program as outlined above. TVA provides an excellent regional setting within which to evaluate existing knowledge about the effects of biomass development and policies toward this development. Clearly, biomass development is occuring and can be expected to continue in the region. In addition, the unique presence of TVA provides significant advantages to the study. TVA represents an existing storehouse of information on environmental conditions in the region and expertise in environmental monitoring and analysis. The active interest of TVA in pursuing biomass development on a regional basis insures the relevance of study results to at least one policy user. Finally, the existence of the regional organization adds to the breadth of the policy options which can be analyzed in this context. It is possible that some biomass development and management options can be implemented within this region more easily than elsewhere. Once demonstrated, however, they may provide useful examples and information to other regions experiencing biomass development.

THE BIOMASS INTEGRATED ENVIRONMENTAL ASSESSMENT

The integrated environmental assessment effort was initially conceived to be implemented in three phases. Phase I is now complete. The Phase II research design is undergoing major revisions and should be finalized and initiated during the Spring of 1981 to continue for approximately two years. A third phase is now considered optional, contingent on the results of Phase II and availability of resources.

Phase I, was a regional overview and planning study of the implications of widespread use of wood as a major energy source within the TVA Region. Because of resource and time constraints, research was limited to wood for energy. Phase II will also deal with other forms of biomass energy, particularly conversion of agricultural products to alcohol fuels.

During this phase the potential for wood development was estimated and a consumption scenario constructed. Secondly, environmental and wood resource constraints were examined on a region-wide basis to identify impact-prone areas ("hot spots") where potential incompatibilities between environmental and physiographic factors, biomass resource, and anticipated levels of development were likely to occur. Phase I also identified a preliminary list of alternative policy strategies that could mitigate or avoid potential environmental problems, defined data bases within TVA that could be supplemented to provide better information about environmental and socioeconomic impacts, and developed a draft plan for integrated assessment of "hot spots" chosen for study in Phase II.

PHASE I RESULTS

During Phase I, potential environmental impacts were assessed on three different levels to provide some of the baseline information on which Phase II could build.

Potential impacts were first identified in general terms and discussed qualitatively. An attempt was made to roughly associate levels of potential environmental impact with given levels of wood energy utilization. Additionally, impacts were estimated regionally on the basis of two biomass penetration scenarios.

The scenarios assumed that wood use for energy would increase roughly two and one-half times between 1980 and 1990 asnd would increase slightly from 1990 to 2000. This would result in an increase in total wood use in the region of 14 million dry ton equivalents (DTE) by 1990 and 15 million DTE by 2000. The scenarios assumed a high, but technically feasible, level of wood use in order to highlight potential consequences. Both scenarios assumed roughly equivalent total wood use but allocated this use according to two variations. One of these emphasized residential wood use while the other emphasized industrial use. Finally, impacts were identified for two impact-prone counties. Hamilton County, Tennessee was chosen as a highuser county and Dade County, Georgia was chosen as a highsupplier county.

In order to identify "hot spots" within the 201-county TVA region that are most subject to environmental degradation from increased harvesting and burning of wood a series of transparent overlays was constructed. The following parameters were considered in constructing the overlays: current violations of air quality standards, air quality maintenance areas, prevention of significant deterioration areas, air pollution potential due to terrain features and meteorological conditions, distribution of soils, landslide potential, flood prone communities, areas with nonpoint source water pollution problems, and projected demand on the forest resource.

Preliminary findings were developed as a result of the Phase I overview in several areas. It was estimated that the volume of wood required to meet the regional demand under the Phase I scenario could be provided without damage to the forest resource if careful management and harvesting techniques are used. The estimated increase in the regional demand could require 14 million dry tons of wood per year by 1990. This is less than half of the estimated volume of wood theoretically available for increased use from annual growth of forests in the region.

Mature forests are among the lowest contributors of sediment to surface waters, and sediment loadings from well managed forests are within the same order of magnitude. However, balloon logging, cable logging and tractor logging may cause increases in loadings of 10, 100, and 1000 times, respectively. In addition to sediment, nutrients and pesticides may also be carried to receiving waters. This is most likely to occur in the vicinity of managed silviculture areas where fertilization and pest control programs are carried out.

A simplified means of estimating potential effects of increased levels of wood harvesting shows that much depends upon the technique used. Assuming that sediment yields from harvested areas increase 10 fold, total sedimentation rates for the entire region would increase 4 to 8 percent. However, assuming a 100-fold increase in sedimentation from harvested areas would cause a 63 to 92 percent regional increase over background levels.

Whether wood harvesting has positive or negative effects on wildlife depends on the type of harvesting and species under consideration. In general, small-scale timber harvesting increases wildlife populations because the early successional stages of a forest support a greater variety of species than large, unbroken tracts of mature timber. The "edge effect" created by a clear cut increases the habitat and species diversity. However, large clear cuts will decrease populations since many species use forests for shelter and will not browse in open areas. Large game animals will benefit from the removal of forest residues, while small mammals and birds will be adversely affected.

Although wood combustion produces generally less of the conventional air pollutants than fossil fuels it replaces, there may be significant air quality problems associated with it. This is of special concern in the residential sector where emissions are unregulated. Increased concentrations of residential wood combustion could contribute to violations of air pollution standards for total suspended particulates when combined with other existing air pollution sources.[15] Also, there is a potential health hazard associated with the emission of polycyclic organic matter.[16] These pollutants are released near the ground, where human exposure may occur before they are dispersed. An unknown fraction may be released indoors where dispersion may be minimal and exposure time during winter months is 14 to 22 hours/day.

There are at least two potential safety problems associated with increased wood use. In the residential sector, wood-burning could increase the danger of fire due improper installation or operation of heating equipment and creosote build-up in chimneys. Also, wood harvesting has historically been a high risk occupation. Between 1976 and 1979, annual occupational injury rate for the wood harvesting industry averaged 26 incidents per 100 full-time workers, compared to an average of 9.25 for all private sectors. Given a projected increase in the regional harvesting work force of 4600 to

7100 full-time employees by the year 2000, a linear extrapolation of accident rates would result in an additional 1150 to 1780 work-related incidents annually. With rapid expansion of the industry, one might expect that much of the labor would be less well trained and that a higher rate of accidents could occur.

These are examples of potential impacts which might develop with rapidly expanding use of wood for energy. The Phase I effort also did some preliminary work toward developing policies to avoid or mitigate those impacts.[17] This work will be emphasized in Phase II.

BIEA Phase I activities have already had an impact on TVA policy. As a result of early information concerning environmental impacts, TVA's residential wood heater promotion program has been restricted from counties which violate ambient air quality standards for TSP and CO and where ample wood resources are not known to exist. There has also been an increase in emphasis placed in commercial and industrial combustion and biomass conversion to liquid fuels. The Phase I document is also serving to provide guidance and scoping for the environmental assessment activities required under the National Environmental Policy Act (NEPA). It is believed that considerable time and money can be saved in meeting the NEPA requirements because of the BIEA activities to date.

PHASE II DESIGN

Early concepts of the Phase II study design emphasized detailed assessments of one or more representative multi-county subregions. It was felt that this subregional approach would force the early "integration" of the various specialized disciplines involved in the study and provide usable results without the time and resources required to assess the entire region in-depth. Another early concept which remains in force is the intent to build on existing data bases, models, ongoing technical research, and in-house expertise available within the TVA base program.

One example is the proposed utilization of TVA's already extensive equipment, data and staff expertise in monitoring, modeling and analysis of air quality problems. In addition, partly as a result of the planning for the BIEA project, a field study has been designed to evaluate local air quality effects from residential wood burning. This study is jointly supported by EPA, TVA and the Department of Energy (DOE) and is currently in progress. It is expected that the results of this study will provide an essential input to the Phase II integrated assessment process. The results of ongong research programs within TVA, EPA and DOE evaluating efficiency and emissions from available wood heating devices under various fuel and operating conditions are also useful input data.

The proposed forestry component of the Phase II effort will build on previous work to develop an automated Forest Resource Information System which utilizes data collected by the U.S. Forest Service and TVA's Forestry Division. This system will assist in analysis of impacts on forest resources under alternative assumptions of demand, forest productivity and management conditions, harvesting techniques, etc.

The analysis of water quality effects of runoff created by certain types of harvesting techniques will build on the adaptation of runoff and water quality models previously developed to evaluate the effects of strip mining of coal and various reclamation techniques. These are a few of the most striking examples of the utilization of existing capabilities in the planned Phase II analysis.

The Phase II study will include an assessment of liquid fuels and will probably not confine all analyses to the same representative multi-county region. This approach will rely on the expertise and analytic abilities of a core team of researchers to integrate results and will allow the analysis of policy issues to be performed on a region-wide basis in Phase II.

The Phase II study will be carried out by an interdisciplinary research team. This team will be managed within TVA's Office of Natural Resoruces (ONR) and will likely include representatives of air quality, water quality, and forestry components of ONR and expertise in biomass technology, agriculture and economic analysis from other parts of TVA. Additionally, other members of TVA staff or outside consultants may be included as other areas of expertise are needed. It is anticipated that the first task of this interdisciplinary team will be to jointly complete the detailed Phase II work plan. The study team will develop a range of scenarios which emphasize wood utilization and alcohol fuels, but will also address the potential for other forms of biomass energy.

Because of the limitations of resources and time available for the Phase II effort, it is expected that interaction with the interested parties will be limited to advisory groups. A number of approaches are being considered for organizing this group or groups. It is expected that membership will include representatives from EPA, Region IV personnel, TVA, appropriate State interests - particularly those dealing with water and air quality, forestry, and agriculture, and constituencies having economic, social, or political interests in potential biomass energy development. Options being considered include the formation of several groups or of a single group with changing membership over time as the study progresses.

EXPECTATIONS FOR THE REMAINDER OF THE PROJECT

The preliminary findings from Phase I of the project indicate some issue areas which will require further attention in the remainder of the study. Other additional areas have already been identified for inclusion in Phase II. Many of these issues are particularly challenging from a policy point of view as they do not appear to be particularly amenable to traditional regulatory approaches. Additionally, the current political climate and public opinion are not particulary favorable to creation of new regulations. This could result in the development of new approaches to the mitigation of environmental hazards. Some of the issue areas which currently appear on the agenda for Phase II will be briefly described with a discussion of some policy options to be evaluated.

A more detailed evaluation will be made of the available techniques for harvesting wood and the effects of alternative techniques on long term forest productivity, wildlife, water quality, etc. In addition, the study will attempt to identify and analyze a range of policy mechanisms to promote the use of environmentally sound methods. In addition to consideration of the potential for regulation at various levels of government, options such as technical assistance and information, voluntary cooperation with private industry, trade associations, etc., will be considered. Safety problems associated with increased logging operations might also be mitigated through voluntary industry cooperation, information, technical assistance, etc.

Environmental effects of wood combustion in industry may be manageable within the existing framework of regulations although additional research may be necessary to develop control technology for non-conventional air pollutants such as organics and to evaluate the costs and effectiveness of such technologies. In the residential sector indoor and outdoor air pollution and fire hazards associated with improper installation or operation of residential wood heating devices could present serious problems. Solutions to these problems are likely to be complex, possibly involving local building codes and inspections, close cooperation with the manufacturers of heating appliances, special approaches in areas which already have air quality problems and consumer information among others.

A range of problems associated with the production and utilization of alcohol fuels will need to be addressed. This area was not emphasized in Phase I. Potential problem areas which must be evaluated include emissions from automobiles using alcohol fuels as well as the impacts of various processes to convert wood or other biomass material to alcohol. One final area of interest is the effects of large scale agriculture to produce crops for energy, particularly the use of previously marginal farmland for this purpose.

It is anticipated that the outputs from Phase II can be used in the formulation of several types of policy for TVA. The first would be a policy which would identify those types of biomass-for-energy technologies TVA would want to encourage through demonstrations or other policies. The second would result in policies which would change, or reinforce TVA natural resource programs to encourage and demonstrate use of the best biomass resource management techniques.

Products of the project will also aid local, state, and other Federal agencies to assess the effectiveness or need of alternative regulations, incentives, or technical assistance programs to stem anticipated adverse consequences of unrestrained biomass-for-energy development.

In addition to the results related to biomass policies specifically, it is expected that the experience gained from the study process, may be of value to TVA. The study will demonstrate a mechanism for drawing together specialists from TVA's staff to provide an interdisciplinery evaluation of a specific problem area. If this demonstration is perceived as successful by TVA, the approach may be applied to other concerns.

The experiment could also have more far reaching demonstration effects. Assessments of this nature have not in the past normally been carried out by researchers on the staff of a large government agency (excepting of course the Congressional Office of Technology Assessment - OTA - which has such studies as its primary function). There may be interest in replicating the TVA "in-house" assessment capability in other government settings.

It is expected by EPA that the study will contribute to the broad objectives of the Integrated Assessment Program described earlier in this paper. The TVA regional assessment will bring together results of technical research programs in TVA, EPA and elsewhere and to convert these results into policy relevant information. One product of the study will also be a clearer definition of additional research needed to support informed policy decisions about biomass development.

Finally, it is expected that the BIEA can develop and evaluate a flexible and creative set of alternative policy approaches to mitigate potential adverse impacts and to promote both rapid and environmentally sound development of this resource. These policy options will undoubtedly contain a complex mix of actions to be taken by various federal government agencies, state, local and regional authorities, private industry and individuals. It is expected that approaches can be found which will allow biomass energy to make a substantial contribution to the energy needs of the region without significant hazards to the environment and public health. The results of the study should also be useful to researchers and decision makers in other regions and at the national level in considering alternative policies toward biomass energy development.

REFERENCES

1. Biomass also includes several additional categories such as aquatic plants, peat utilization and plant fluids but these are not expected to play a major role in this study.

2. See for example, The Nation's Energy Future, A Report to the President of the United States, 1 December 1973, submitted by Dr. Dixy Lee Ray, Chairman, U.S. Atomic Energy Commission; and Report to the Interagency Work Group on Health and Environmental Effects of Energy Use, November, 1974, Prepared for the Office of Management and Budget; Council on Environmantal Quality, Executive Office of the President.

3. Report to the Interagency Work Group. Ibid.

4. For more details on the Integrated Assessment Program see Plotkin, Steven E., "EPA's Integrated Assessment Program" in Health, Environmental Effects and Control Technology of Energy Use, U.S. Environmental Protection Agency, Report #600/7-76-002, 1976 p. 328-333, and Reznek, Steven R., "Integrated Technology Assessment" in Energy/Environment II, U.S. Environmental Protection Agency, Report No. EPA-600/9-77-012, 1977, p. 207-219.

5. Organizations within the U.S. normally use the TA terminology while internationally SAT seems more prevalent. There is no apparent substantive difference between the two.

6. Coates, J.F., "The role of Formal Models in Technology Assessment", Technological Forecasting and Social Change, Vol. 9, 1976, p. 139-190.

7. See Porter, A.L., et al., A Guidebook for Technology Assessment and Impact Analysis, New York: Elsevier North Holland, Inc., 1980, Chapter 8 for a description of this activity.

8. Hetman, F., "Social Assessment of Technology and Some of Its International Aspects", Technological Forecasting and Social Change, Vol. 11, 1978, p. 303-313.

9. See for example, Smith, L.F., "Electric Utility Energy Systems Integrated Technology Assessment", in Energy/ Environment II, U.S. Environmental Protection Agency, Report No. EPA-600/9-77-012, 1977, p. 243-252.

10. Results of these studies are presented in: White, I.L., et. al., Energy from the West: Summary Report, U.S. Environmental Protection Agency, Report No. EPA-600/9-79-027, August 1979, and Ohio River Basin Energy Study: Main Report, and Ohio River Basin Energy Study: Project Summary, U.S. Environmental Protection Agency, forthcoming. All reports may be requested from: Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

11. In fact, it is actually the point of integrated assessment, or technology assessment, to identify potential future conditions which are undesirable and to make possible their avoidence, ensuring that these projected futures do not become actual.

12. For more detailed discussions of the models and other available techniques for TA see: Coates, 1976, op. cit., Porter 1980, op. cit., and Coates, J.F., "Technology Assessment -- A Tool Kit", Chemtech, June 1976, p. 372-383.

13. The difficulties and benefits of this approach are discussed in more detail in White, I.L., "An Interdisciplinary Approach to Applied Policy Analysis," Technological Forecasting and Social Change, 15, 1979, p. 95-106.

14. This program is under the overall direction of John Stinson, Program Manager, Office of Agricultural and Chemical Development, Tennessee Valley Authority, Muscle Shoals, Alabama.

15. Duncan, J.R., K.M. Morkin, and M.P. Schnierbach., Air Quality Impact Potential from Residential Wood-Burning Stoves, Tenessee Valley Authority, Muscle Shoals, Alabama, 1979, and Tong, E.Y., A. Hirata, and B.L.

Niemann, *Regional Air Quality Assessment for the Tennessee Valley Authority: Task 2: Air Quality Assessment of Inereased Wood Burning*. Teknekron Research, Inc., Report No. RM-033-TVA-79/R1, Prepared for the Tennessee Valley Authority, September, 1979.

16. De Angeles, D.G., D.S. Ruffin, and R.B. Reznek, *Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment*, U.S. Environmental Protection Agency, Report No. EPA-600/7-80-040, March 1980 and, U.S. Department of Energy, *Health Effects of Residential Wood Combustion: Survey of Knowledge and Research*. DOE/ EV-0114 UC-586. Assistant Secretary for Environment, Office of Environmental Assessment, Washington, D.C., 1980.

17. Results of Phase I of the BIEA are reported in more detail in Aubuchon, V.R., *Biomass Integrated Environmental Assessment: Phase I Project Summary* and Krickenberger, K., et. al., *Biomass Integrated Environmental Assessment: Phase I Report*, U.S. Environmental Protection Agency, forthcoming.

Session 2: ASSESSMENTS OF RESIDENTIAL WOOD HEATING EFFICIENCY AND EMISSIONS

Chairman: Jerome P. Harper
Tennessee Valley Authority
Chattanooga, TN

RESIDENTIAL WOOD HEATING EFFICIENCY AND EMISSIONS - AN OVERVIEW

by: Jerome P. Harper
Supervisor, Solar Test Facility
Solar Applications Branch
Tennessee Valley Authority
Chattanooga, Tennessee

ABSTRACT

Presented is an overview of some of the major factors related to the determination of the efficiency and emissions of residential wood heating appliances. Topics discussed include current techniques for determining efficiency, methodologies for emission measurements, interrelationships between efficiency and emissions, and operational and design factors. The paper is intended to provide introductory material for Session 2 - Assessments of Residential Wood Heating Efficiency and Emissions.

INTRODUCTION

The efficiency and emission measurements from residential wood heating devices are interrelated subjects. Typically, systems with high combustion efficiency are those systems which generate less pollutants, and some efficiency tests rely on determining the flue gas emissions. This interrelationship is important since many measurement techniques for determining flue gas composition exist. The purpose of this paper is to discuss some of the current approaches for determining wood heater efficiency and for the measurement of wood heater emissions and to discuss the interrelationship among these types of measurements and factors which affect them.

EFFICIENCY DETERMINATIONS

There are two primary methods for measuring the efficiency of a residential wood heating device, namely the stack loss method and the calorimeter room approach (1) (2) (3). The stack loss or indirect method is the more traditional. It is a method which is based on determining the combustion efficiency of the device and sensible and latent heat losses out of the flue. One reason for the popularity of this approach is that it is relatively simple to perform. Flue gas temperature, the percent of carbon monoxide, carbon dioxide, and oxygen, in the flue gas are the basic measurements which need to be made in the stack loss approach.

However, there are some problems with applying this approach for determining wood heater efficiencies as it was primarily developed to evaluate steady state burn conditions. One problem with the stack loss method is that stochiometric burning does not occur. The smoke, particulate matter, and creosote produced during wood combustion testifies that complete conversion of the carbon in the wood to carbon monoxide, or carbon dioxide does not occur. Also, since pyrolysis, as well as combustion, occurs in wood heaters, the complete conversion of the fuel bound hydrogen to water does not take place.

Another problem is that the wood fuel composition changes during the burn cycle and calculating combustion efficiency using a fixed fuel composition may not be the best approach. Also, ambient conditions around the wood heater must be controlled because combustion air temperature affects both the combustion and heat transfer efficiency. Thus, all the chemical and thermal losses must be properly considered in the stack loss method when it is applied to wood combustion systems. Efficiency determinations made using this technique, therefore, must be carefully evaluated on the basis of the flue gas measurement technique used and the test and analysis conditions.

The calorimeter room method is a direct approach that measures the heat output of the wood heater. Essentially the heat gain in a small room is measured over a period of time. The calorimeter room must have a low infiltration, good insulation, and be constructed of a material with a low heat capacity such that thermal storage of the heat released by the stove is minimized.

Air exchange between calorimeter room and the outside environment is critically important. Temperature differences between the outside and the inside, as well as pressure differences, make controlling the amount of air and its flow through the room a critical parameter in the design and operation of these testing devices. If the air exchange is too great, the convective heat transfer of the wood heater is affected. If the balance is improper, excessive sensible heat loss up the flue is highly probable. The accuracy of a calorimeter room depends greatly upon its instrumentation and its thermal response time. It is very important in this approach to reduce the transient response between generation of the heat by the stove and its measurement.

Both efficiency measurement techniques have their respective positive points. The stack loss method of efficiency determination generates a considerable amount of data concerning both the combustion efficiency and heat transfer capabilities of the wood heater, as well as giving an estimate of its overall efficiency. The calorimeter room technique perhaps provides a more direct method of evaluating the overall efficiency of the wood heater as defined by heat output rather than the heat loss, but does not typically provide the insights on combustion efficiency and heat transfer efficiency. Improvements in the stack loss method by utilizing continuous monitoring equipment for measurement of the main flue gas constituents, CO_2, CO and O_2 and the continuous measurement of total hydrocarbons, NO_x, and water in the flue gas can greatly refine this technique to yield true instantaneous efficiencies such that the performance over the wood burn cycle could be evaluated as a function of time rather than only over the whole burn cycle.

EMISSION MEASUREMENTS

Measurement of emissions (i.e., flue gas constituents) is a very controversial subject, particularly when it relates to environmental regulation. Thus, the approved techniques for determining emissions are subject to environmental review by the Federal Government and are published in the Federal Register. (4) Some relevant EPA methods for measuring emissions are EPA Method 3 for the determination of CO, CO_2, and O_2, EPA Method 5 for the determination of particulate matter, EPA Method 6 for the measurement of sulfur dioxide and EPA Method 7 for measurement of nitrogen oxides.

The basic approved methods involve discreet or grab-type samples and have been developed for steady state burn conditions. However, EPA does approve continuous monitoring instrumentation as an equivalency method alternative for emissions measurements. Current studies on wood heater emissions have either used primary discreet sampling techniques, (5) or other continuous measurement instrumentation (6) (7).

Emissions from wood heaters are different from those found from conventional combustion sources such as power boilers, and gas and oil furnaces. Measurement techniques and the definitions derived for conventional sources may be inappropriate for wood heaters. For example, most organic gases in wood flue emissions are very condensable and discrimination of the lighter hydrocarbon fraction is difficult. If EPA Method 5 or the SASS approach to sample particulates is used, the data obtained contain significant portions of hydrocarbons in both the filterable and condensable fractions. Thus, discrimination between gaseous and particulate hydrocarbons becomes a function of the operational conditions, sampling method, analysis method and interpretation.

Standard emission measurement techniques are difficult, if not impossible, to apply to wood heaters. For example, stack velocity measurements are important in determining emission factors but are very difficult to make in small diameter flues with low flows. This situation stresses the reliability of the standard manometric approach for stack velocity using an inclined or micro-manometer and virtually eliminates the potential for isokinetic sampling. Complicating the stack velocity determinations in wood heaters is the condensable fraction that often collects on the pitot tube changing the orifice size and changing the accuracy and precision of the measurement technique.

Thus, emission measurement techniques for evaluating wood heating appliances cannot readily be adapted from conventional source testing approaches. Many grab sample approaches, such as orsat, may also be inappropriate because of the transient and nonsteady state burn conditions existing in these appliances. Sampling techniques which extend over the duration of the cycle are often too insensitive to be useful for precise studies of pollutant formation phenomena and are often problematical because of difficulties with condensables when sampling over extended periods. Continuous monitoring offers an alternative for evaluating wood heater emission which is responsive to changing flue gas conditions thereby permitting a better analysis of pollutant formation as it pertains to actual conditions in the wood heater.

TEST CONDITIONS

Irrespective of the method utilized when measuring efficiency or emissions, it is the test conditions which must influence the outcome. Testing is done on a system and the wood heater is only one component of the actual system's design. Chimney design, height, and materials of construction also determine what the efficiencies and/or resultant emissions may be. The operation of the wood heater (e.g., burn rate) also affect test measurements by changing the flue gas conditions. Therefore, when evaluating a testing approach, it is very important that system design and operation be considered in the interpretation of the data.

Fuel composition, moisture content, and also size are very significant test variables. Wood is a complex fuel and the combined processes of combustion and pyrolysis which occur in a wood heater are critically affected by changes in the composition of the fuel, moisture content, and the effective burning surface area.

Therefore, test conditions must be very well defined if reproducable and comparative test methodology are to be developed for determining either efficiency or emissions in conventional residential wood heating devices.

SUMMARY

Emission measurements are interrelated to efficiency determinations in that an acceptable methodology for flue gas analysis is important to both. The methodologies that are employed for either efficiency or emissions determination greatly affect the accuracy of the results that will be obtained. Flue gas analysis techniques provide data which is useful for the determinations of either efficiency or emissions. The continuous measurement of flue gas composition may be the preferred approach for wood heaters because they tend to be more responsive to transient changes in flue gas composition experienced during the burn cycle. Also, instantaneous determination of efficiency or emissions would be possible giving better insight on thermal processes and pollutant formation which are continually ongoing and changing during the burning cycle in a wood heater.

REFERENCES

(1) Shelton, J.W. et. al., "Wood Stove Testing Methods and Some Preliminary Experimental Results," ASHRAE Transactions Vol. 48, Part I, (1978).

(2) Fireplace Institute, "Test Standard for Rating Wood-Fired, Closed Combustion - Chamber, Heating Appliances," Chicago, Illinois (1979).

(3) Fireplace Institute, "Test Standard for Rating Wood-Fired, Open Combustion - Chamber, Heating Appliances," Chicago, Illinois (1979).

(4) Federal Register, Vol. 42, No. 160, PP. 41768-41789, (Thursday, August 18, 1977).

(5) De Angelis, D.G., et. al., "Preliminary Characteristics of Emissions From Wood-Fired Residential Combustion Equipment," EPA-600/7-80-040, (March, 1980).

(6) Harper, J.P. and C.V. Knight, "Factors Affecting Wood Heater Emissions and Thermal Performance," Proceedings of Seventh National Conference on Energy and the Environment, Phoenix Arizona, (December, 1980).

(7) Allen, J. and M. Cooke, "Control of Emissions from Residential Wood Burning by Combustion Modification (Draft)," Battelle Columbus Laboratories, EPA Project Summary Report, (October 31, 1980).

WOOD COMBUSTION EMISSIONS AT ELEVATED ALTITUDES

by: J.A. Peters, T.W. Hughes, and D.G. DeAngelis
Monsanto Research Corporation
Dayton, Ohio 45407

ABSTRACT

Combustion of wood in fireplaces and in wood-burning stoves is growing in popularity as the cost for other fuel sources increases. The growing use of wood combustion for aesthetic and primary and secondary home heating has attracted wide spread environmental concern due to increased particulate, carbon monoxide and polycyclic organic material (POM) emissions over other residential fuel types. A recent study conducted for the U.S. Environmental Protection Agency indicated that residential wood combustion is the largest stationary source of POM emissions. Recently, high levels of particulates and POM's have been found in mountainous resort areas. Local EPA officials are concerned that woodstoves operated at high elevations result in significantly higher pollutant emissions than stoves operated at lower elevations. The EPA conducted a study quantifying high elevation emissions; this paper presents the results of the study.

INTRODUCTION

As North Americans turn increasingly to wood heating equipment, a new problem is arising -- the possibility of increased levels of air pollution from wood burning in stoves and fireplaces. The potential effects of such burning on air quality is of particular concern in EPA Region VIII, where residential wood burning for home heating and for aesthetic reasons is increasing in the ski resort areas. One location mentioned repeatedly is Vail, Colorado, a major Rocky Mountain ski resort, where a haze blankets the valley town each evening. It was felt that the reason for the problem was the near simultaneous lighting of hundreds of après-ski blazes in condominium fireplaces and wood-burning stoves [1].

An earlier study was conducted by Monsanto Research Corporation (MRC) to determine the environmental impact of residential wood combustion equipment [2, 3]; however, the emission testing and data collection were carried out under low altitude conditions. Since combustion processes and associated emissions often differ at different altitudes, it could not be assumed that existing data from near sea level are applicable to the high altitude Region VIII communities. An earlier study [4] conducted in Vail, Colorado by PEDCo-Environmental, Inc. indicated that emission factors from residential wood combustion at higher altitudes differed from those at lower altitudes by a factor of two or more.

The objective of this sampling program was to determine whether emissions from operating a wood stove at high altitude differ from those at low altitude. The low altitude data from the previous MRC study was used for comparison. Accordingly, test conditions duplicated the previous study, with altitude as the only variable which was changed.

EXPERIMENTAL

DESIGN

The sampling program was designed to duplicate the earlier, low altitude study -- in particular, the emission test runs on a nonbaffled airtight stove burning seasoned red oak. Under the low-altitude study a matrix of test conditions was set up involving three types of combustion devices burning four types of wood. One of the twelve test conditions was strictly duplicated: identical stove, wood type, wood moisture, size of logs, fuel bed configuration, wood burning rate, stack gas flow rate, height of sampling ports above stove, and sampling methods and equipment. Also available for comparison was an emission test run on a stove conducted by PEDCo in their Vail sampling program. Table 1 illustrates the experimental design scheme for analysis comparison.

TABLE 1. HIGH ALTITUDE WOOD STOVE TEST COMPARISON PROGRAM
(Number of samples collected and analyzed)

MRC-High altitude		MRC-Low altitude		PEDCo-High altitude	
Front-half particulates	Condensable organics	Front-half particulates	Condensable organics	Front-half particulates	Condensable organics
4	2	2	1	1	1

Also collected were samples for polycyclic organic material (POM), which also yield front-half particulates, and carbon monoxide, which can vary over an order-of-magnitude throughout the burn of one charge of wood.

METHODS

The nonbaffled stove was an air-tight, boiler plate radiant heater. The combustion zone dimensions are approximately 0.61 m high, 0.4 m wide, and 0.71 m long. Two air inlets are located on the door of the stove. This unit, shown in Figure 1, weighs approximately 160 kg (350 lb), and was also lined with firebrick. The stove tested and associated flue pipe were mounted on a mechanical scale to provide readout of mass. Weights were taken prior to and immediately after charging wood to determine the mass of wood charged. A weight reading was also taken at the start-up and shut-down of sampling for emission factor calculations. Burning rate was maintained by readings at 10-minute intervals.

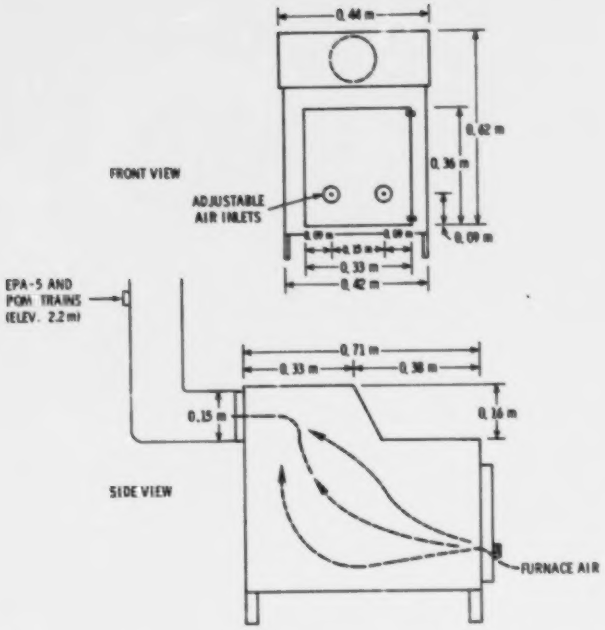


Figure 1. Nonbaffled airtight stove showing generalized combustion-air flow pattern.

As a precaution against sampling probes affecting weight readings, the sampling trains were suspended by cables and balanced. A difference of less than 0.05 kg influence was shown with the sampling train in place.

Time of sampling spanned at least one wood charge to the stove. Steady state burning conditions were sampled rather than stove start-up or burn-down conditions, as in the MRC-low altitude and PEDCo-Vail studies.

Particulate emissions (front-half filterable and condensable organics) were collected by EPA Method 5. A back-up filter was inserted between the third and fourth impinger, as shown in Figure 2. Particulate emissions (front-half filterable only) and POM's were collected with a modified Method 5 sampling train, which adds an XAD-2 resin trap between the filter box and impinger system. A cooler trap (empty impinger) is inserted prior to the resin cartridge to reduce the gas temperature to 21°C before entry into the resin for increased collection efficiency. A schematic of the train and sample recovery procedure is given in Figure 3. Single point sampling with the probe tip placed in the stack center was used because flat velocity profiles have been demonstrated on solid fuel residential heating devices [5]. Isokinetic sampling rates were maintained.

RESULTS

The results of MRC's high altitude particulate and carbon monoxide emission testing are given in Table 2. Excellent control over the wood burning rate was exercised among the four test runs, as demonstrated by a standard

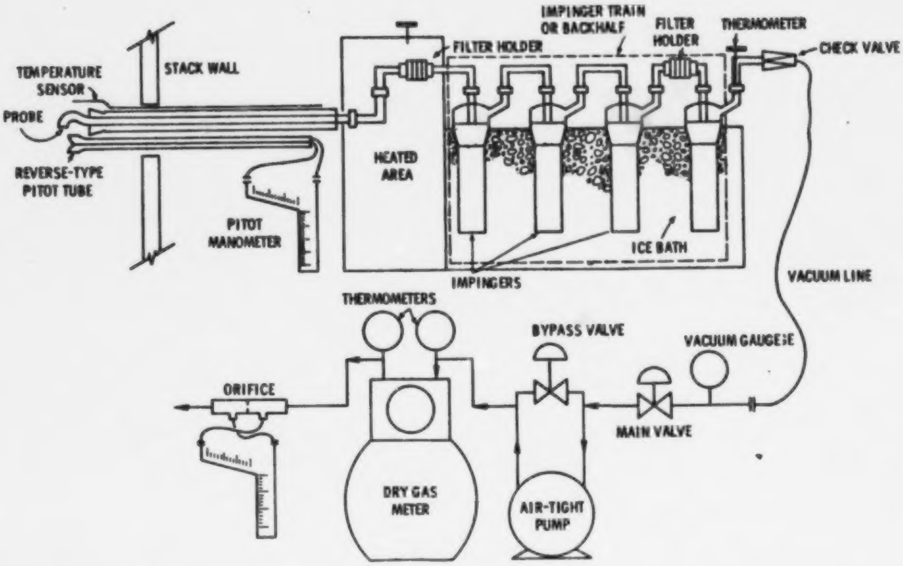
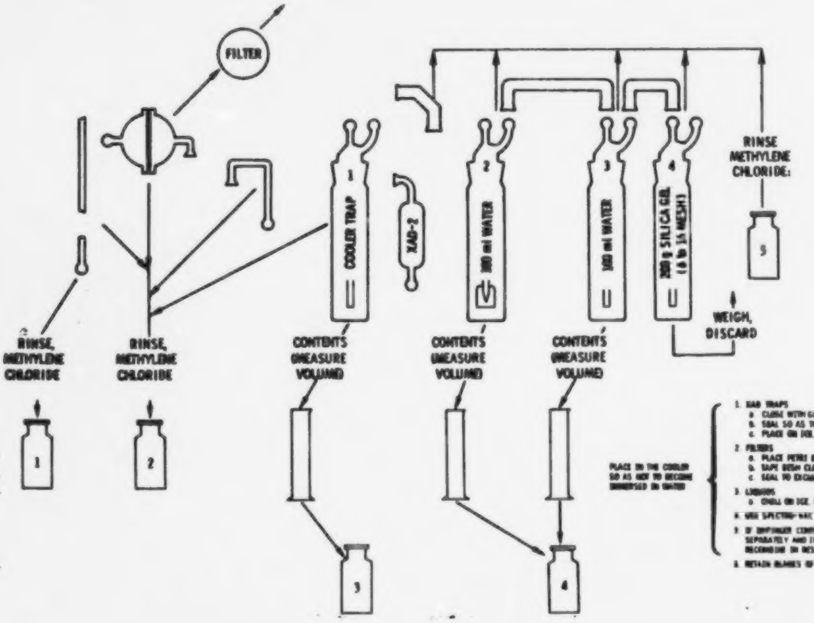

IMPINGER TRAIN OR BACKHALF
FILTER HOLDER
THERMOMETER
CHECK VALVE
FILTER HOLDER
TEMPERATURE SENSOR
STACK WALL
PROBE
REVERSE-TYPE PITOT TUBE
HEATED AREA
PITOT MANOMETER
ICE BATH
IMPINGERS
VACUUM LINE
THERMOMETERS
BYPASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
DRY GAS METER
AIR-TIGHT PUMP

Figure 2. Schematic of EPA Method 5 sampling train with back-up filter for particulate and condensable organic material collection.


FILTER
1
COOLER TRAP
XAD-2
2
100 ml WATER
3
100 ml WATER
4
200 g SILICA GEL (6 to 16 MESH)
RINSE METHYLENE CHLORIDE
5
RINSE, METHYLENE CHLORIDE
RINSE, METHYLENE CHLORIDE
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
WEIGH, DISCARD
1
2
3
4

PLACE IN THE COOLER SO AS NOT TO BECOME IMMERSED IN WATER

1. XAD TRAPS
   a. CLOSE WITH GLASS CAPS AND PINCH CLAMPS
   b. SEAL SO AS TO EXCLUDE WATER
   c. PLACE ON ICE, EXCLUDING LIGHT
2. FILTERS
   a. PLACE PETRI DISH, TOP SIDE UP
   b. TAPE DISH CLOSED
   c. SEAL TO EXCLUDE WATER. CHILL, EXCLUDE LIGHT
3. LIQUIDS
   a. CHILL ON ICE, EXCLUDE LIGHT
4. USE SPECTRO-VAC GREASE THROUGHOUT
5. IF IMPINGER CONTENTS ARE MULTIPHASE, MEASURE SEPARATELY AND IDENTIFY AS TO ORDER OF LAYERS RECORDED IN RESPECTIVE SAMPLE BOTTLE
6. RETAIN BLANKS OF FILTER XAD AND ALL REAGENTS

Figure 3. Schematic of POM train components and sample recovery.

TABLE 2. SUMMARY OF HIGH ALTITUDE WOOD STOVE PARTICULATE EMISSION RESULTS AND COMPARISON DATA

Description (68°F)	Units	MRC-High altitude					MRC-Low altitude			PEDCo
		POM 1	POM 2	EPA5-1	EPA5-2	Avg.	POM	EPA5	Avg.	EPA5
Barometric pressure	in Hg	24.62	24.69	24.65	24.59	24.64	29.4	29.3	29.35	21.58
Vol dry gas sampled	dcf	16.65	18.18	19.38	15.33	17.39	30.9	39.9	35.4	28.9
Stack gas moisture	%	5.61	12.71	20.43	12.06	12.70	20.24	11.42	15.83	5.01
Stack temperature	°F	464	512	516	480	493	713	722	718	415
Stack flow rate (dry std)	dscfm	33	33	27	27	30	35	32	33.5	63.1
Stack flow rate (actual)	acfm	74	84	76	67	75.3	98	83	90.5	152
Particulate loading (front)	gr/dscf	0.2166	0.2351	0.2359	0.1697	0.2143	0.1986	0.0823	0.1405	0.1408
Particulate loading (back)	gr/dscf	*	*	0.3324	0.3965	0.3645	*	0.2426	0.2426	0.5756
Particulate loading (total)	gr/dscf	*	*	0.5683	0.5662	0.5788	*	0.3249	0.3249	0.7164
Emission rate (front)	lb/hr	0.062	0.067	0.054	0.040	0.056	0.059	0.023	0.041	0.076
Emission rate (back)	lb/hr	*	*	0.077	0.093	0.085	*	0.066	0.066	0.311
Emission factor (front)	g/kg	4.9645	3.846	3.687	2.419	3.729	3.1	1.9	2.5	5.557
Emission factor (back)	g/kg	*	*	5.015	5.645	5.330	*	6.0	6.0	22.74
Burning rate	kg/min	0.094	0.130	0.113	0.124	0.115	0.144	0.915	0.118	0.103
Excess air	%	46.6	16.2	41.5	72.4	44.2	25.0	25.0	25.0	47.1
CO Emission factor	g/kg	273	270	**	0	181	***	***	230.5	219

*No back-half condensable organics are measured with the POM train.

**No sample taken.

***Average is the result of 10-minute interval samples.

deviation for the burning rate of ±14% of the mean value. The high altitude tests' burning rate nearly duplicated the low altitude burning rate, differing by only 2.5% for the averages. Particulate emission rates (front-half filterables) also showed good repeatability between runs, with a standard deviation which was only ±28% of the mean value. Thus replicate runs at a fixed burning rate will give repeatable particulate emission rates by EPA Method 5 for a given stove and wood type.

The small differences in emission factors between MRC's high and low altitude emission test runs are attributed to the difference in ambient air temperature and, hence, stove inlet air temperature. During the low altitude testing the room temperature was 70-75°F versus 49°F for the high altitude test. This is shown in the large difference between stack gas temperature at the sampling point -- 493°F vs. 718°F. Cooler stove inlet air may tend to "quench" combustion in and above the flame zone in the stove and increase filterable particulate emissions to a small degree.

CONCLUSIONS

A comparison between the high altitude and low altitude emission tests leads one to the conclusion that, when the operating variables are held constant, there is no statistically significant difference in particulate or CO emissions. So why, then, are the results of the PEDCo emission tests three times as high?

A major aspect of the PEDCo-Vail study was the absence of weight determinations for the burning rate calculations. It should be pointed out that "the amount of wood burned during a test run could only be estimated because the amount remaining at the end of test could not be weighed [4]." An eyeball estimate of the wood charge left in the stove (or fireplace) at a run's end based on the apparent volume will tend to bias the error in weight determination toward the low side, and, hence, inflate the emission factor. The filterable particulate stack gas concentration for PEDCo's test was within the same range as either MRC study. PEDCo's stove had a higher stack gas flowrate, probably due to more inlet air admitted. Tables 3 and 4 summarize the test conditions and test results.

The PEDCo test had much greater condensable organic emissions -- 0.311 lb/hr vs. 0.085 lb/hr for MRC's study. This was due probably to two main reasons: PEDCo burned dry pine and burned it at a lower temperature. The use of pine, a more resinous wood, can have an increased effect on emissions over the use of a hardwood such as oak. MRC's low altitude study found that condensable organic emissions doubled (to 10-12 g/kg) when burning green pine but the results did not indicate that for dry pine. However, the MRC low altitude study had greater stack gas temperatures (700°F vs. 415°F) which indicate a higher stove combustion zone temperature. In the PEDCo-Vail stove test, the stack temperature was measured at the stove exit. The stove inlet temperature was unusually low (similar to the MRC high altitude tests) at 50°F. Thus it was likely that the lower combustion zone temperature created more unburned volatiles which were "quenched" by the cool inlet air rising above the combustion zone. Also, because of the weight estimates for unburned wood charge, it is likely that PEDCo's reported burning rate was lower and the emission

TABLE 3. COMPARISON SUMMARY OF WOOD STOVE EMISSION TEST CONDITIONS

Description (68°F)	Units	MRC-High altitude	MRC-Low altitude	PEDCo-Vail
Barometric pressure	in Hg	24.64	29.35	21.58
Ambient temperature	°F	40	75-80	50
Wood type		Seasoned oak	Seasoned oak	Seasoned pine
Burning rate	kg/hr	6.9	7.1	6.2
Excess air	%	44.2	25.0	47.1
Stack temperature	°F	493	718	415
Stack flowrate (dry std)	dscfm	30.0	33.5	63.1
Stack flowrate (actual)	acfm	75.3	90.5	152

TABLE 4. COMPARISON SUMMARY OF WOOD STOVE EMISSION RESULTS

Description (68°F)	Units	MRC-High altitude	MRC-Low altitude	PEDCo-Vail
Particulate loading (front)	gr/dscf	0.2143	0.1405	0.1408
Particulate loading (back)	gr/dscf	0.3645	0.2426	0.5756
Particulate loading (total)	gr/dscf	0.5788	0.3249	0.7164
Emission rate (front)	lb/hr	0.056	0.041	0.076
Emission rate (back)	lb/hr	0.085	0.066	0.311
Emission rate (total)	lb/hr	0.141	0.107	0.387
Emission factor (front)	g/kg	3.73	2.50	5.56
Emission factor (back)	g/kg	5.33	6.00	22.74
Emission factor (total)	g/kg	9.06	8.50	28.30
CO Emission factor	g/kg	181	230.5	219

factor became inflated. Butcher has shown, with his own particulate sampling system, that particulate emission rates are inversely proportional to burning rate [6].

ACKNOWLEDGMENTS

This work was supported by the Food and Wood Products Branch, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, and EPA Region VIII, Denver, Colorado, under contract 68-03-2550. Paul de Percin was the project officer, and Paula Machlin of Region VIII and Michael Osborne of IERL in Research Triangle Park, North Carolina provided valuable input and guidance.

REFERENCES

1. Romero, A. E., R. M. Buchman, and D. G. Fox. A study of air pollution from fireplace emissions at Vail Ski Resort, J. Environ. Health, 41(2): 117-119 (1978).

2. DeAngelis, D. G., D. S. Ruffin, and R. B. Reznik. Preliminary characterization of emissions from wood-fired residential combustion equipment. Research Triangle Park, NC: U.S. Environmental Protection Agency; 1980 March. 158 p. EPA-600/7-80-040.

3. DeAngelis, D. G., D. S. Ruffin, J. A. Peters, and R. B. Reznik. Source assessment: residential combustion of wood. Research Triangle Park, NC: U.S. Environmental Protection Agency; 1980 March. 99 p. EPA-600/2-80-042b.

4. Source testing for fireplaces, stoves, and restaurant grills in Vail, Colorado. Contract 68-01-1999, U.S. Environmental Protection Agency, Region VIII, Denver, Colorado. (Draft document submitted to the EPA by PEDCo-Environmental, Inc., December 1977.) 29 p.

5. DeAngelis, D. G., and R. B. Reznik. Source assessment: coal-fired residential combustion equipment field tests. Research Triangle Park, NC: U.S. Environmental Protection Agency; 1977 June. 81 p. EPA-600/2-78-004c.

6. Butcher, S. S. Particulate emissions from wood burning and the implications for health. Presented at the 73rd Annual Meeting of the Air Pollution Control Association, June 22-27, 1980, Montreal, Quebec, Paper No. 80-22.5. 8 p.

RESIDENTIAL INDOOR AIR QUALITY AND WOOD COMBUSTION

by: D.J. Moschandreas
J. Zabransky, Jr.
H.E. Rector
GEOMET Technologies, Inc.
1801 Research Boulevard
Rockville, Maryland 20850

ABSTRACT

Data from suburban residences in the Boston metropolitan area reveal a potential adverse impact on indoor air quality from woodburning in woodstoves and fireplaces. Ambient pollutant concentrations at each residence were compared to corresponding pollutant levels indoors at three locations (kitchen, bedroom and activity room). Individual gaseous pollutant samples were averaged on an hourly basis while 24-hour integrated samples of particulate matter were obtained. Ten gaseous pollutants were sampled along with total suspended particulates (TSP). Chemical analyses further determined ten components of TSP including trace metals, benzo-a-pyrene (BaP), respirable suspended particulates (RSP), and water soluble sulfates and nitrates. Monitoring lasted two weeks at each residence and was conducted under occupied, real-life, conditions.

Observed, elevated indoor concentrations of TSP, RSP and BaP are attributed to woodburning. Data indicate that average indoor TSP concentrations during woodburning periods were about three times corresponding levels during nonwoodburning periods. The primary 24-hour national ambient air quality standard (NAAQS) for TSP was exceeded once indoors during fireplace use, and the secondary, 24-hour TSP NAAQS was also exceeded indoors by RSP concentrations. Indoor BaP concentrations during woodstove use averaged five times more than during nonwoodburning periods. At this stage, results are only indicative, but the potential impact from elevated indoor concentrations of TSP, RSP and BaP, attributed to woodburning, may have long-term health implications.

INTRODUCTION

Recent findings indicate that air quality indoors, where an individual may spend as much as 85 percent of his day, may be as important a health factor as outdoor air quality (Moschandreas and Morse, 1979; Spengler, et al, 1979; Fanger and Nolbjorn, 1979; and others). The national policy to conserve energy by reducing the air infiltration rate of residences has precipitated a series of studies regarding the effect of such a measure on the indoor residential air quality (Yocum, 1970; Hollowell, et al, 1978; Moschandreas, et al, 1978; Moschandreas, et al, 1980; Spengler, et al, 1979; Repace and Lowrey, 1980; and others). The national desire to conserve energy has also led to a rapidly expanding search for renewable sources of energy. Specifically, the resurgence of woodburning as a supplemental source of home heating may be a significant factor in determining the character of the residential air quality. Modifications and attachments to fireplaces have converted these facilities from recreational items to functional indoor heat sources. In addition, 1.2 million woodstoves were sold in 1979; these sales are on an upward trend (Fireplace Institute, 1980).

A field monitoring program designed to compare indoor and outdoor air pollution at ten residences and two office buildings was undertaken in the Boston metropolitan area. Three of the monitored residences used either a woodstove or fireplace in the course of their respective sampling periods. By examining the air quality levels during woodburning and nonwoodburning periods, it is possible to distinguish the air pollutants which may be attributed to emissions from wood combustion.

EXPERIMENTAL

The three dwellings selected for this study are detached residences: the residence with a woodburning stove, denoted as Residence A, is a fifteen year old split level structure; Residence B is a thirty-year old cape cod house with a fireplace, and Residence C is a fifty-year old woodframe structure which also has a fireplace. Air infiltration rates averaged 0.68, 0.65 and 1.24 air changes per hour for Residences A, B and C respectively. Dwellings are considered tight if the air infiltration rate is less than 0.5 ach; loose dwellings have air infiltration rates above 1.0 ach.

Each site was monitored while normal occupant activity was ongoing; monitoring lasted two weeks at each residence. Data were sampled in three indoor locations (zones) at each site and one outdoor location adjacent to each building. Indoor zones at residences included the kitchen, master bedroom and an activity room, usually the living room. In Residence A, the woodstove was located in the basement, immediately below the sampled living room zone. The fireplaces in Residences B and C were both located in the activity room that was sampled.

Air was sampled in each of the four sampling zones for various pollutants. Gas phase sampling consisted of a four-minute integration preceded by a one-minute line purge. Gas phase sampling was performed three times each hour for each zone. The results were then accumulated as (arithmetic) hourly average concentrations. Measurements for particulate matter consisted of 24-hour integrated samples taken in the same four locations. These measurements were supported by various meteorological observations as well. Table 1 lists all pollutants and other supporting parameters measured in this study.

TABLE 1. POLLUTANT AND METEOROLOGICAL PARAMETERS MONITORED

Gaseous Pollutants (Hourly Concentrations) ppm	Particulate Matter (24-Hour Concentrations) ($\mu g/m^3$)		Meteorological Parameters (Hourly Readings)
NO	TSP		Wind speed (mph)
NO_x	RSP (<3.5 μm)		Wind direction (deg. azimuth)
CO_2	BaP*		Temperature (°C)
CO	SO_4 from TSP		Relative Humidity (%)
O_3	NO_3 from TSP		Air Infiltration Rates (Intermittent)
SO_2	Pb	from TSP	Tracer (SF_6)
CH_4	Fe		Dilution Technique
THC	Mn		
	V		
	As		
	Cd		

* BaP units in (ng/m^3)

RESULTS

The complete data base generated from this study consists of detailed time variations of all pollutants monitored (Moschandreas, et al, 1980). In general, the behavior of indoor pollutant concentrations is associated with corresponding outdoor levels and indoor activity. Results obtained for TSP, RSP, BaP and selected gaseous pollutants illustrate this association in terms of woodburning activities.

TOTAL SUSPENDED PARTICULATE (TSP) MATTER

The average and range of TSP concentrations and the ratio of indoor to outdoor measurements, taken in the three subject residences, are shown in Table 2. One woodburning day was registered in each of the residences with a fireplace (Residence B and Residence C). The indoor 24-hour TSP concentrations during these woodburning days are higher than the average 24-hour TSP indoor concentrations on nonwoodburning days by approximately a factor of three. The indoor, 24-hour TSP concentrations on woodburning days are also higher than the maximum indoor levels observed in each residence during nonwoodburning days. Moreover, the indoor 24-hour, integrated TSP samples taken at Residences B and C, during fireplace use, exceed the primary and secondary National Ambient Air Quality Standards (NAAQS), respectively. Significantly, these standards are not exceeded on nonwoodburning days. Finally, the indoor-outdoor contrast, denoted by the in/out ratio, for days with and without woodburning activity strongly suggests that the fireplace is a major source of indoor particulate emissions.

TABLE 2. INDOOR-OUTDOOR 24-HOUR TSP CONCENTRATION CHARACTERISTICS OF WOODBURNING AND NONWOODBURNING DAYS

		TSP ($\mu g/m^3$)					
		Woodburning			Nonwoodburning		
Residence	Location	Average	In/Out Ratio	Range	Average	In/Out Ratio	Range
Residence A	In	85.1	1.8	32.5 - 180.6	28.3	1.0	13.6 - 42.0
	Out	46.5		10.0 - 79.5	28.9		10.7 - 60.2
Residence B	In	267.0	6.1	Only One Woodburning Day	81.0	2.1	31.2 - 137.5
	Out	44.0			38.1		12.3 - 140.5
Residence C	In	183.6	8.5	Only One Woodburning Day	52.8	1.5	24.8 - 116.2
	Out	21.6			35.3		17.4 - 57.3

Only Residence B is occupied by smoking residents, the proportion of TSP attributed to smoking in this residence is very small because the occupants are light smokers. Fewer than 10 cigarettes were consumed in this house on any day. The contrast between indoor levels, measured in the living room, and outdoor levels during woodburning and nonwoodburning days indicates emissions from a major indoor source. The lack of other identifiable major sources of TSP suggests a cause-and-effect relationship between the woodburning activity and elevated levels of particulate matter.

The impact of an active woodstove on indoor TSP concentrations is indicated in Figure 1. TSP measurements show indoor and outdoor levels as a function of woodburning (WB) and nonwoodburning (NWB) days. Indoor-outdoor correspondence suggests that during nonwoodburning days the indoor levels can be equal to, higher than, or lower than corresponding outdoor levels. However, of the nine woodburning days, eight displayed higher indoor levels than corresponding outdoor levels. Depending on the magnitude of the woodburning activity, the indoor levels may be higher than corresponding outdoor levels by as much as a factor of four. On Day 3 the secondary 24-hour TSP NAAQS was exceeded indoors during woodburning. Unfortunately, the daily log kept by the occupants of the residence did not specify the quantity or the kind of wood burned.

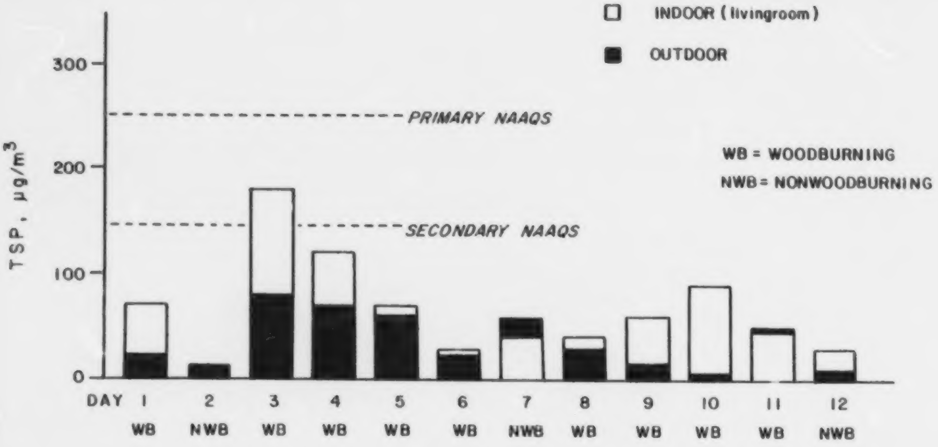


FIGURE 1. INDOOR AND OUTDOOR 24-HOUR TSP CONCENTRATIONS AT RESIDENCE A

RESPIRABLE SUSPENDED PARTICULATE (RSP) MATTER

A summary of RSP data, similar to that presented for TSP, is given in Table 3 for the woodburning residences. For purposes of this study, particulate matter having diameters less than 3.5 µm will be considered RSP. RSP concentrations are naturally lower than TSP levels, but the relative magnitudes in each category follow the TSP data closely. The 24-hour indoor RSP concentrations on woodburning days are higher than the maximum observed indoor levels on nonwoodburning days. Indoor and outdoor RSP concentrations are comparable on nonwoodburning days except at Residence B where smoking occurred on all monitoring days. On nonwoodburning days the indoor RSP contribution from smoking is about 25 µg/m^3, thus the impact of woodburning on RSP concentrations is readily distinguished from cigarette smoking at Residence B and is roughly four times greater. Moreover, the TSP, 24-hour secondary ambient standard (150 µg/m^3) was exceeded indoors by RSP concentrations at Residence B during the woodburning period in the fireplace.

TABLE 3. INDOOR-OUTDOOR 24-HOUR RSP CONCENTRATION CHARACTERISTICS OF WOODBURNING AND NONBURNING DAYS

		RSP (µg/m^3)					
		Woodburning			Nonwoodburning		
Residence	Location	Average	In/Out Ratio	Range	Average	In/Out Ratio	Range
Residence A	In	49.0	1.4	14.3 - 72.5	28.0	1.0	23.9 - 31.6
	Out	34.2		22.6 - 57.6	27.4		13.9 - 53.7
Residence B	In	159.9	5.3	Only One Woodburning Day	40.9	2.9	21.7 - 66.9
	Out	30.3			14.0		7.3 - 21.8
Residence C	In	67.6	11.3	Only One Woodburning Day	18.8	1.1	6.3 - 39.0
	Out	6.0			17.9		7.7 - 30.5

TYPING GUIDE SHEET

Finally, the relative indoor emission of RSP from fireplaces is clearly illustrated by the magnitude of the in/out ratio of 24-hour RSP concentrations at Residences B and C. The impact of woodstove operation on indoor RSP concentrations is evident but reduced compared to the fireplaces because of the closed combustion chamber design of the stoves. Figure 2 displays the impact of an active woodstove on indoor RSP levels.

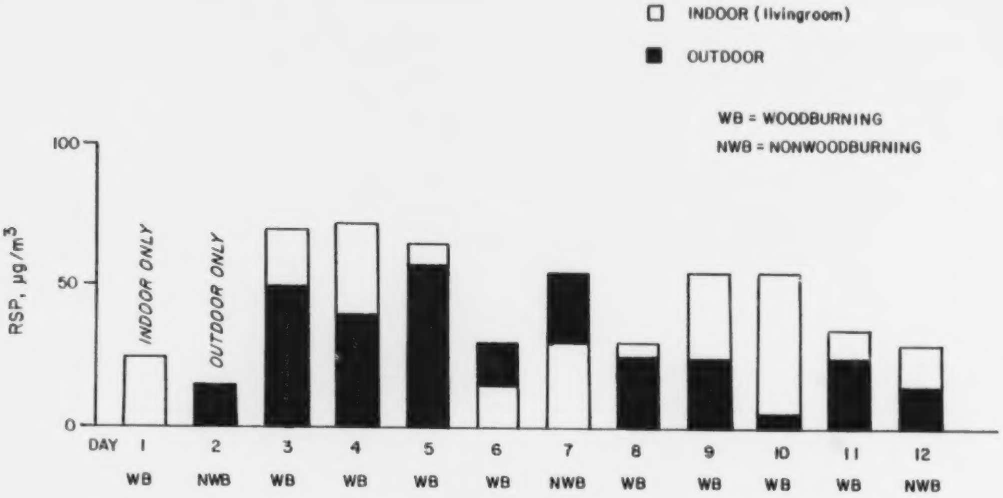


FIGURE 2. INDOOR AND OUTDOOR 24-HOUR RSP CONCENTRATIONS AT RESIDENCE A

BENZO-A-PYRENE (BaP)

Of particular interest is the indoor behavior of benzo-a-pyrene (BaP), a by-product of wood combustion and known carcinogen. BaP data were obtained only for Residences A and B. Indoor and outdoor BaP concentrations at Residence A are given in Figure 3, on woodburning and nonwoodburning days. Woodburning episodes occurred during nine out of eleven days of sampling. Indoor BaP concentrations on woodburning days averaged about five times higher than on days when the woodstove was not in use. Excepting one day, outdoor levels of BaP were relatively low.

The single woodburning episode in Residence B increased BaP concentrations by an order of magnitude above the average of levels found on nonwoodburning days. The BaP concentration on the woodburning day was 11.4 ng/m^3, the average concentration during twelve days with no woodburning activity was 0.6 ng/m^3. The outdoor levels of BaP were consistently lower than indoors and relatively low in magnitude.

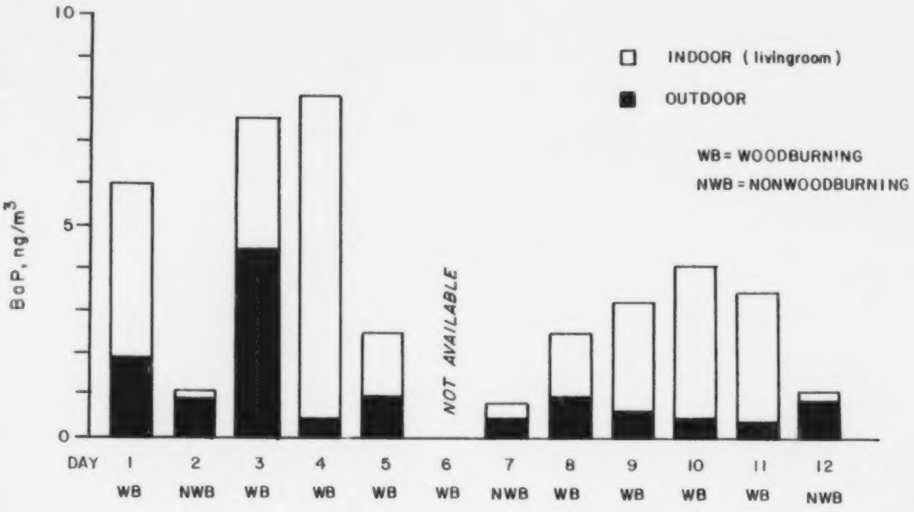


FIGURE 3. INDOOR AND OUTDOOR 24-HOUR BAP CONCENTRATIONS AT RESIDENCE A

The significance of elevated BaP during woodburning activity can readily be interpreted from Table 4 which gives examples of indoor and outdoor BaP concentrations at several residences. Gas facilities for heating and cooking do not appear to significantly impact indoor BaP levels. A slight increase of indoor BaP is noticeable in the residence with combined smoking and gas facilities. Residences with all electric facilities seem to have slightly higher indoor BaP concentrations, but it must be emphasized that our data base was too small to test for the significance of these differences. Moreover, an analysis of the BaP concentration ranges suggests that there is little or no difference, indoors, among all the residences except when woodburning occurs; outdoor variations have been taken under consideration in this analysis. Particularly, Table 4 shows that ambient BaP concentrations in heavy industrial U.S. cities averaged 1.2 ng/m^3 on an annual basis while a comparable statistic for rural areas was about 0.1 ng/m^3. The indoor 24-hour average for BaP concentrations at the woodstove residence was 4.7 ng/m^3 on woodburning days, nearly five times the urban ambient average.

TABLE 4. TYPICAL 24-HOUR INDOOR AND OUTDOOR BAP CONCENTRATIONS (NG/M^3) AT VARIOUS RESIDENCES IN THE BOSTON METROPOLITAN AREA (URBAN AND RURAL AMBIENT VALUES ARE PROVIDED FOR COMPARISON)

Residence Type	Indoor BaP (ng/m^3)		Outdoor BaP (ng/m^3)		Reference
	Mean	Range	Mean	Range	
Gas Facilities (Nonsmoking)	0.4	0.1 - 0.6	0.5	0.1 - 2.2	Moschandreas, et al, 1980
Gas Facilities (Smoking)	0.9	0.4 - 1.8	0.4	0.1 - 1.4	Moschandreas, et al, 1980
Electric Facilities (Nonsmoking)	1.1	0.2 - 2.8	0.9	0.3 - 2.2	Moschandreas, et al, 1980
Electric Facilities Woodstove No Woodburning	1.0	0.3 - 1.1	0.8	0.7 - 0.8	Moschandreas, et al, 1980
Woodburning	4.7	2.3 - 8.0	1.3	0.2 - 4.2	Moschandreas, et al, 1980
U.S. Cities with Coking Ovens (1975) (~4000 samples)			1.2	0.3 - 4.7	Suta, 1978
U.S. Rural (1975) (~600 samples)			<0.1	<0.1	Suta, 1978

GASEOUS POLLUTANTS

Woodburning appears to have an impact on indoor CO concentrations. Specifically, a detailed and typical time variation of CO concentrations, associated with woodburning and no woodburning activity, is shown in Figure 4. The time series represents average hourly indoor and outdoor concentrations over a three-day period. The daily activity questionnaire kept by the occupants shows that during the first two days, the woodstove was loaded and stoked four times; the first time was a cold firing. During the hour following successive reloadings and stoking, the carbon monoxide level rose substantially and then decayed. The CO increases were probably associated with back drafts when the woodstove was opened for refueling. After the stove was restoked at 1500 hours on the second day, it was left to burn out. During the last 24-hour period no woodburning occurred, and the CO concentration record was devoid of the structure indicated in the previous two days. It is significant to note that indoor carbon monoxide levels measured in Residence A, an all electric residence with woodstove, were comparable to CO levels generally found in residences with major carbon monoxide sources such as gas cooking and heating facilities. No other gaseous pollutant monitored in the study showed a strong association with woodburning indoors (Moschandreas, et al, 1980).

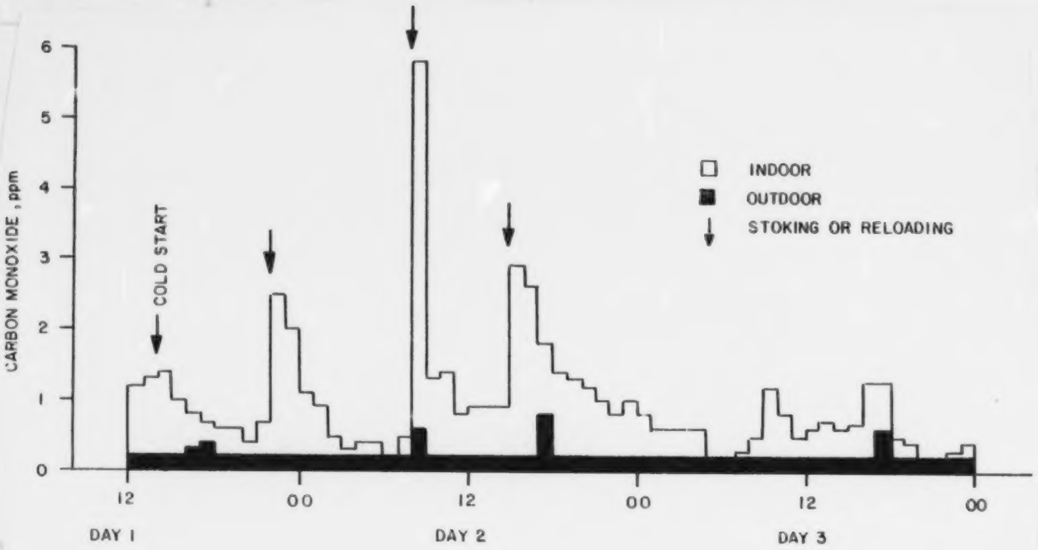


FIGURE 4. CARBON MONOXIDE CONCENTRATIONS AT RESIDENCE A ON THREE SUCCESSIVE DAYS

DISCUSSION

The data discussed here represent a very small portion of the total data base collected as part of the comparative indoor-outdoor study in the Boston area. Woodburning was only one of several indoor pollution sources considered in this study. Conclusions reached should only be considered indicative because of the limited number of woodburning episodes. It should be noted that higher levels than the ones reported in this study would be expected if sampling had occurred in the room where the woodstove was located (Residence A).

Woodburning appears to be a major source of particulate matter emissions within the residential environment. Consequently, woodburning activity may lead to elevated indoor concentrations of TSP, RSP and BaP that would be a significant factor in human exposure.

REFERENCES

Fanger, P.O. and O. Valbjorn, eds. Indoor Climate (proceedings of the First International Indoor Climate Symposium in Copenhagen, Denmark, August 30-September 1, 1978). Danish Building Research Institute, Copenhagen, Denmark, 1979).

Fireplace Institute, 1980. Personal communication from S. O'Roarke, Public Relations Officer, June, 1980.

TYPING GUIDE SHEET

Hollowell, C.D., and G.W. Traynor, 1978. "Combustion Generated Indoor Air Pollution." Presented at the 13th International Symposium on Atmospheric Pollution, Paris, France, April 26-29. Prepared by Lawrence Berkeley Laboratory, Berkeley, California.

Moschandreas, D.J., J.E. McFadden and J.W.C. Stark, 1978. "Indoor Air Pollution in the Residential Environment - Volumes I and II" GEOMET Report No. EF-688, GEOMET, Incorporated, Gaithersburg, Maryland (EPA Report No. EPA-600/7-78-229a and b).

Moschandreas, D.J. and S.S. Morse, 1979. Air Quality in Energy Conserving Residences, GEOMET Report Number ES-772, GEOMET, Incorporated, Gaithersburg, Maryland.

Moschandreas, D.J., J. Zabransky and D.J. Pelton, 1980. Comparison of Indoor-Outdoor Concentrations of Atmospheric Pollutants, GEOMET Report No. ES-823, GEOMET, Incorporated, Gaithersburg, Maryland.

Repace, J.L. and A.H. Lowrey, 1979. "Indoor Air Pollution, Tobacco Smoke and Public Health," Science, v. 208, p. 464, May 2, 1980.

Spengler, J.D., B.G. Ferris, D.W. Dockery, 1979. "Sulfur Dioxide and Nitrogen Dioxide Levels Inside and Outside Homes and the Implications on Health Effects Research," Environmental Science and Technology, v. 13, p. 1276-1280, October, 1979.

Suta, B.E., 1978. "Human Population Exposures to Coke-Oven Atmospheric Emissions," Center for Resource and Environmental Systems Studies, Menlo Park, California. CRESS Report No. 27, October, 1978.

Yocum, J.E., W.A. Cote, and W.L. Clink, 1970. "A Study of Indoor-Outdoor Air Pollutant Relationships - Volumes I and II," Research Corporation of New England, Hartford, Connecticut. NTIS Publication No. PB-195-338.

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD BEGIN SECTIONS HERE

PERFORMANCE OF DOMESTIC WOOD-FIRED APPLIANCES

by

A.C.S.Hayden* and R.W.Braaten**

ABSTRACT

The Canadian Combustion Research Laboratory (CCRL) has developed an indirect or stack loss method to measure the performance of domestic wood-fired space heaters, giving detailed information on operating characteristics and emissions as well. Flue gas composition, including CO2, CO, O2, HC and NOX as well as temperatures and the fuel burning rate are monitored continuously over the burning cycle on a data logging system and stored on magnetic tape for computer retrieval and analysis. This allows an accurate reconstruction of the burning cycle and complete detail on appliance performance over that cycle.

Results of experiments on a series of appliance types are presented. These show that a freestanding fireplace is extremely inefficient in utilizing the potential energy in the wood, while a well designed and well-constructed controlled combustion unit can have efficiencies comparable to a fossil-fuel fired appliance.

---

*Research Scientist and ** Research Engineer, Canadian Combustion Research Laboratory, Energy Research Laboratories, CANMET, Energy,Mines & Resources Canada, 555 Booth Street, Ottawa, Canada K1A OG1.

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY EPA FORM 2350)
TYPING GUIDE SHEET

109

INTRODUCTION

The use of wood for domestic heating is becoming common in many parts of the United States and Canada. Projected continued price increases and supply difficulties for conventional domestic heating fuels (oil and natural gas),as well as the perceived attractiveness of using a potentially renewable energy source, indicate the trend to wood heating is likely to continue.

At the same time, there is increasing concern over the emissions from domestic wood-fired appliances. Incompletely burned gases and condensed liquids cause environmental concern downstream from the source, as well as posing safety hazards for the occupants of the dwelling itself, in the form of toxic carbon monoxide or combustible "creosote". These incomplete products of combustion also represent an efficiency loss, so that reducing these emissions can contribute to more efficient use of wood energy.

This paper describes briefly the continuous heat loss test procedure used by the Canadian Combustion Research Laboratory (CCRL) to measure solid fuel-fired appliance performance, and examines the effect of various designs on performance, both in terms of efficiency and emissions.

APPLIANCE EFFICIENCY

In most oil and gas fired heating equipment, combustion is effectively complete. Combustion Efficiency, the measure of degree of completeness of combustion, is nearly always greater than 99.6%. For wood-fired appliances, combustion is much less complete, and combustion efficiency can be lower than 95%.

Appliance Efficiency is the measure of the ability of the heating appliance to extract heat from the burning wood and combustion products and supply this to the area to be heated. A detailed description of various methods to measure appliance efficiency is given in Reference 1.

Determination of the appliance efficiency of a wood-fired space heater is complicated by the fact that the rate of fuel consumption (burning rate) and the fuel composition (ultimate analysis) vary continuously over the burning cycle. Heat may also be given of the the area to be heated, as well as being lost up the chimney some time after combustion has been completed. The direct measure of appliance efficiency, using a calorimeter room, allows for comparative ratings of heat output between different appliances, but gives no indication for the reasons for good or bad performance, or even what level of combustion performance is being achieved. The method is of little help to the designer in attempting to improve his product.

The indirect method, adopted by CCRL,measures all the energy going up the chimney in the form of heat losses. It can be used in the laboratory or, with some adaptation, in the field, and does provide detailed information on the combustion performance of an appliance. However, it requires care on the part of the user if useful information is to be obtained. Detailed experimental data from flue gas analyzers, preferably on a continuous basis, is required. Because of the potenially large amount of "dirty" gases due to incomplete combustion, the sampling techniques employed require careful filtering and handling of the gases.

APPLIANCE TYPES

Wood space heating appliances, commonly called wood stoves, can be divided into to major classifications, airtight and non-airtight or, more properly, controlled and uncontrolled combustion. Controlled combustion appliances (airtights) can be further subdivided into several types depending on the flow of gases within the combustion chamber. Five types considered in this paper are as follows.

FREESTANDING FIREPLACE

This is still the most common type of wood-fired appliance, although it is now recognized to have a very low heating efficiency. Field tests reported by CCRL in Reference 1 show that a conventional built-in fireplace can actually increase oil consumption while the fireplace is being used. In this paper, the fireplace tested is a freestanding conical type, shown schematically in Figure 1. There is no controlled combustion air delivery, the only control being a damper downstream of the appliance. The unit is not airtight. There is no internal baffling to aid in combustion or heat transfer.

UPDRAFT (BOX) STOVE (AIRTIGHT)

This type has controlled combustion air, coming in from the top, front or side. However, there is no significant internal baffling within the combustion chamber, and the flame has direct access to the flue pipe, as shown in Figure 2.

HORIZONTAL (S) BAFFLE STOVE (AIRTIGHT)

This appliance is illustrated in Figure 3. It has an internal horizontal baffle running from the rear of the appliance below the flue exit to at least mid-length. The combustion air intake is controlled, usually at the front. The wood tends to burn at the front while "smoke", released at the rear, remote from the flame, is forced back under the baffle towards the flame. The flue gases then travel back above the baffle to the appliance exit.

DOWNDRAFT STOVE (AIRTIGHT)

This appliance is illustrated in Figure 4. The conbustion air is controlled and the fuel sits on a grate. When the appliance is fired, a vertical damper is opened at the rear top, so that the unit initially behaves like an updraft, to promote rapid combustion. When a hot bed of coals is developed, this damper is closed; the flue gases are then forced back down through the bed of coals before going up out out the flue exit.

SIDEDRAFT STOVE (AIRTIGHT)

This appliance is illustrated in Figure 5. There is a vertical baffle, open at the bottom 4-6 cm, and an open/shut damper at the top, similar to the Downdraft. This damper is open when combustion is initiated, to generate

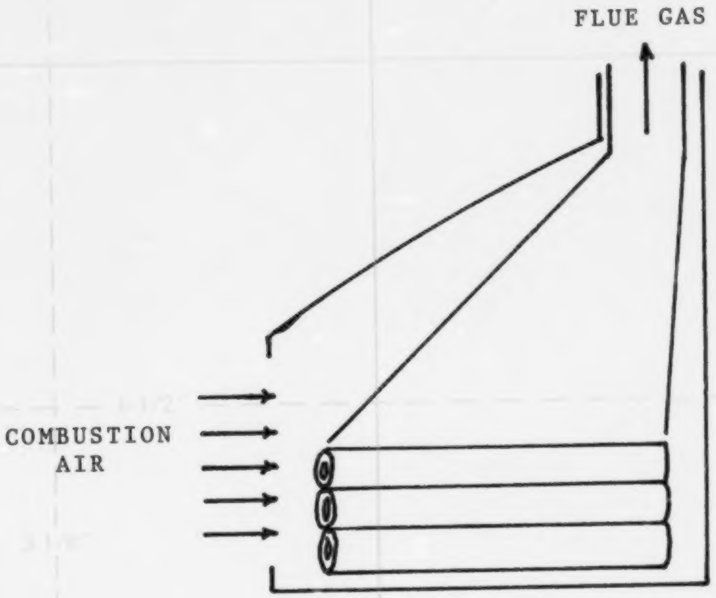

FLUE GAS
COMBUSTION AIR

Figure 1. Schematic of freestanding fireplace.

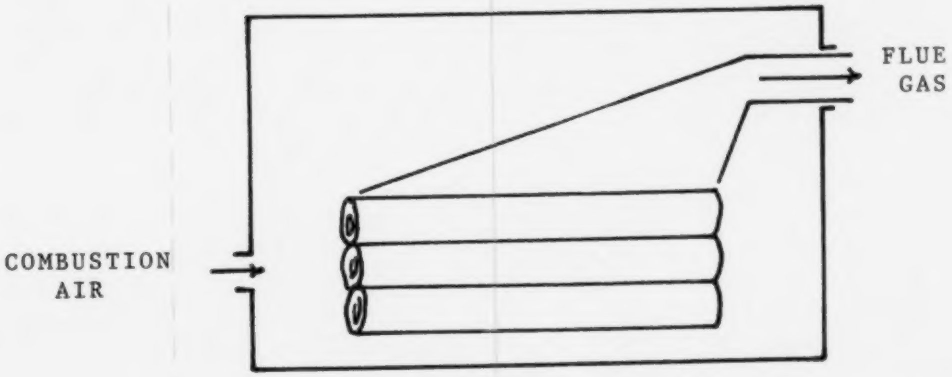

FLUE GAS
COMBUSTION AIR

Figure 2. Schematic of controlled combustion updraft heater.

EPA Form 2350-6 (4-80)
(PREVIOUSLY CIN: EPA FORM 287)
TYPING GUIDE SHEET

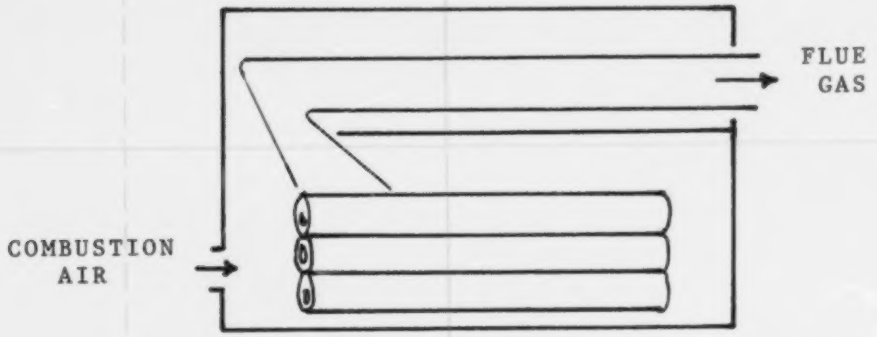

FLUE GAS
COMBUSTION AIR

Figure 3. Schematic of controlled combustion horizontal baffle heater.

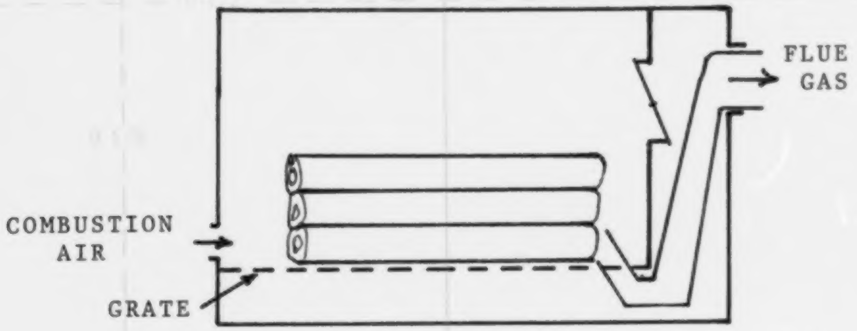

FLUE GAS
COMBUSTION AIR
GRATE

Figure 4. Schematic of controlled combustion downdraft heater.

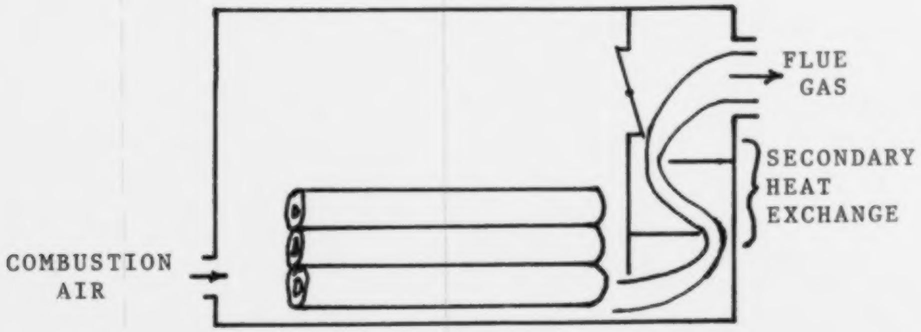

FLUE GAS
SECONDARY HEAT EXCHANGE
COMBUSTION AIR

Figure 5. Schematic of controlled combustion sidedraft heater.

hot coals and adequate draft. The damper is then closed. The gases must move down under the vertical baffle, the flame is developed horizontallly to the fuel bed, and the gases and flame ideally come in contact at the baffle point before passing up through a heat exchanger and out the flue exit.

TEST PROCEDURE

The test results presented in this paper are based on laboratory trials at CCRL using an indirect heat loss method, details of which are given in Reference 1. The appliance is installed on a digital weigh scale and all significant flue gas properties are recorded continuously on a data logging system and magnetic tape. Carbon dioxide and carbon monoxide are measured on NDIR analyzers, oxygen by both paramagnetic and ZrO_2 systems, nitrogen oxides by chemiluminescence, total hydrocarbons with a heated FID and temperatures with CrAl thermocouples. With the recording system, complete scans are made every ten seconds over the burning cycle. A detailed profile of the performance of the appliance can thus be easily reconstructed and analyzed.

Results reported herein were obtained using a seasoned split hardwood, sugar maple, with mean moisture content of 16%. Ultimate analysis of this fuel is presented in Table 1. Use of a common hardwood assures appliance output representative of real-life conditions, but can result in variations between seemingly identical runs on the same appliance.

FIRING RATES

In selecting firing rates for test purposes, likely field-use rates should be considered. Wood stoves are most often used as space heaters, providing heat to only a portion of a dwelling, due to difficulties in distributing the heat. Even the upper limit of heat output requirements, that of supplying all the home's heat requirements, varies greatly depending on design, size, orientation, level of insulation and location in the country.

Data gathered from field trials on oil-heated homes in Ottawa, Canada, as presented in References 2 and 3, indicate that for a heating season of 4670 Celsius degree-days, average heating requirements are only 15 Mjoules/hour, with peak demands in the order of 47 Mjoules/hour. Hence, stove operation in the output range of 10 to 20 Mjoules/hour is most likely to provide representative data, even for this relatively cold area.

TEST RESULTS

The following results are typical of several burns on each of the five appliance types. For the updraft (box) type, which represents the largest number of stoves on the market, the range of typical performance results which might be expected in this category are reported as updraft I and updraft II.

EFFECT OF BURN RATE

The effect of operating the same controlled combustion horizontal baffle appliance at different burn rates is presented in Table 2. As the burn rate

TABLE 1. SUGAR MAPLE ULTIMATE ANALYSIS (DRY BASIS)

Component	% by weight
Carbon	49.6
Hydrogen	5.2
Sulphur	0.1
Nitrogen	0.2
Ash	2.0
Oxygen	43.0
Gross Calorific Value	8300 Btu/lb
Moisture Content	16%

TABLE 2. EFFECT OF FIRING RATE ON EFFICIENCY AND EMISSIONS,HORIZONTAL BAFFLE.

Burn Rate kg/h	Excess Air	Stack Temperature °C	Carbon Monoxide Emissions %v/v	Carbon Monoxide Emissions g/kg wood	HC Emissions g/kg wood	Combustible Loss %	Efficiency %	Heat Output Mj/h	Emissions per Output, g/Mj CO	Emissions per Output, g/Mj HC
1.15	363	44	0.79	165	39	14.5	75.9	13.5	16.4	3.8
1.78	258	67	0.87	140	33	12.3	76.2	21.2	13.3	3.1
3.66	209	150	0.95	108	25	9.5	60.0	40.0	11.2	2.6

TYPING GUIDE SHEET

was increased by 55% from the base level of 1.15 kg/hour, excess air fell by 29% and the mean stack temperature over the cycle increased from a low 44°C to 67°C. With the decreased excess air, mass emissions of incomplete products of combustion fell, although the volumetric measurement of emissions increased. Overall efficiency first rose slightly with increase in firing rate, but with a threefold increase in firing rate, the greatly increased stack temperature offset the reductions in excess air and incomplete combustion, and the efficiency was 6% lower.

Increased burn rate resulted in a continual decrease in emissions of carbon monoxide and hydrocarbons, when compared both on a mass per unit fuel input and mass per unit heat putput basis.

It is interesting to note that the actual volumetric carbon monoxide emissions increase with burn rate. However, since this is a percentage of the total volumetric dry flue gas, a quantity which falls with excess air at increased burn rates, mass emissions decrease.

EFFECT OF APPLIANCE DESIGN

For typical heat output rates, Table 3 summarizes test results for four of the appliance types: freestanding fireplace, updraft, horizontal baffle and sidedraft.

The distortion of apparent CO levels with excess air is particularly apparent with the freestanding fireplace. Although the measured level of carbon monoxide of only 0.07% by volume appears very low, the very high excess air level at which this appliance operates results in the second highest level of CO mass emissions per pound of fuel burned. If someone intends this unit to be used as a heat source in the home, it may be more pertinent to consider the emissions on a mass per heat output basis. In such a case, the CO emissions are more than twice that of any other appliance in this group.

Appliance design appears to have a significant effect on both emissions and efficiency. The relatively sophisticated sidedraft design has only 56% of the CO emissions of the two updrafts, while operating at 16% higher efficiency. While the efficiency of the horizontal baffle design is about the same as the sidedraft, this is achieved by having a lower stack temperature countering a higher degree of incomplete combustion products. Thus the horizontal baffle stove operating at this high efficiency will be more prone to condensation of volatile hydrocarbons in the exhaust, and hence creosote, as well as having higher emissions than the sidedraft.

The two examples of updraft appliance represent the range of results possible within this large classification. While the emissions on a mass per unit fuel burned may be lower for some updrafts than for a horizontal baffle, the lower efficiency of this design results in higher mass emissions on a heat output basis.

In Table 4, performance of four appliance types are compared at higher heat output rates. Two updraft designs showing the range are included. For this design, the two varied greatly in terms of excess air operation and

TABLE 3. EFFECT OF APPLIANCE DESIGN ON EFFICIENCY AND EMISSIONS, MODERATE FIRING RATE.

Appliance Type	Burn Rate kg/h	Excess Air %	Stack Temperature °C	CO Emissions		HC Emissions g/kg	Combustible Loss %	Efficiency %	Heat Output Mj/h	Emissions per Output, g/Mj	
				%v	g/kg					CO	HC
Fireplace	2.64	1863	92	.07	177	42	15.6	24.5	10.0	52.1	12.2
Updraft I	2.37	657	122	.67	184	43	16.3	58.0	21.2	22.9	5.4
Updraft II	2.45	576	124	.45	129	30	11.3	62.9	23.8	14.8	3.5
Horizontal Baffle	1.78	258	67	.87	140	33	12.3	76.2	21.2	13.3	3.2
Sidedraft	1.46	157	122	.81	87	20	7.7	76.7	17.3	8.2	1.9

TABLE 4. EFFECT OF APPLIANCE DESIGN ON EFFICIENCY AND EMISSIONS, INCREASED FIRING RATE.

Appliance Type	Burn Rate Kg/h	Excess Air %	Stack Temperature °C	CO Emissions		HC Emissions g/kg	Combustible Loss %	Efficiency %	Heat Output Mj/h	Emissions per Output, g/Mj	
				%v	g/kg					CO	HC
Updraft I	4.02	436	223	.47	116	27	10.2	56.5	35.1	14.8	3.5
Updraft II	4.05	153	139	.79	153	36	13.5	71.1	44.5	15.5	3.7
Horizontal Baffle	3.66	209	150	.95	108	25	9.5	69.9	40.0	11.2	2.6
Downdraft	4.46	62	117	2.37	169	40	14.9	72.4	49.9	16.8	4.0

and efficiency. However, the emissions per unit heat output were nearly the same. The horizontal baffle appliance had about 25% lower emissions and the same efficiency as the better updraft, in spite of its higher stack temperature and excess air levels. This indicates that the horizontal baffle design would likely have less tendency to creosote than even the better updraft. The downdraft design, which many might consider to be the most sophisticated stove type, and most likely candidate for success, gave disappointing results. Its fairly high efficiency was counterbalanced by the highest emissions levels in this grouping. These may be partially explained by the fact that the appliance was operating near the low end of its output range. Other tests conducted by CCRL indicate that it is most comfortable operating at a burn rate of at least 10 kg of wood per hour. This yields a heat output in the range of 90 Mjoules/hour, far in excess of most homes' requirements. It is unfortunate that a much smaller unit operating with this combustion principle was unavailable, to determine if the results are typical of this design.

CONCLUSIONS

1. Freestanding fireplaces are very inefficient. At the same time, they have high emission rates when expressed as a function of heat output.
2. For controlled combustion wood space heaters, efficiency appears to be maximized within a small range for any specific appliance model.
3. Emissions tend to decrease with increased firing rate.
4. Well-designed sidedraft units appear more efficient than other designs.
5. Emission levels of incomplete combustion products are related to design, particularly when expressed as a function of heat output. Emission factors of a sidedraft type are less than half those of an updraft, while the horizontal baffle puts out only 70% of the updraft emissions.
6. The largest variation in efficiency occured not between appliance types, but rather between different models of the updraft design.
7. The performance of various heaters within a given type will vary depending on how the particular design utilizes the potential performance advantages offered by its type.
8. Reductions in the emissions of incomplete combustion products likely mean reduced creosote formation in flue pipes and chimneys. If this reduction allows higher flue gas temperatures for a given efficiency and heat output, creosote formation will be further reduced.

REFERENCES

1. A.C.S.Hayden, "Efficiency of Wood-Fired Appliances", prepared for CWEI course manual, Installation, Operation and Maintenance of Wood-Burning Appliances, Report ERP/ERL 78-82, CANMET, Energy,Mines & Resources Canada, October 1978.
2. A.C.S.Hayden, R.W.Braaten & T.D.Brown, "Oil Conservation in Home Heating", ASME Journal of Engineering for Power, Vol.99, Ser.A,No.3, July 1977.
3. A.C.S.Hayden et al, "Emissions and Energy Conservation in Residential Oil Heating", Journal of Air Pollution Control Association,V.28,No.7,July 1978

AN ASSESSMENT OF THE EFFICIENCY AND EMISSIONS OF TEN WOOD FIRED FURNACES

by: Robert J. Brandon, P. Eng.
Institute of Man and Resources
Charlottetown, P.E.I., Canada

ABSTRACT

Significant use of wood for residential space heating will require development of improved combustion systems that approach the operational attractiveness of oil or gas fired equipment. Seven innovative wood fired residential central heating systems, together with three conventional wood furnaces, were installed and operated in single family homes over the 1979/80 heating season in a demonstration funded by the Canada-P.E.I. Agreement on Renewable Energy Development. Four of the systems use chip wood fuel and one uses pellet wood fuel; two of the systems involve the use of water thermal storage. During the heating season, thermal performance evaluation and emission testing were carried out on all ten units.

A high volume sampling technique was used to collect flue gas at the chimney exit, enabling particulates and condensable organics to be trapped in a glass fibre filter. Average particulate emission factors ranged from a low of 0.72 g/kg in the case of the wood pellet stoker to a high of 38.6 g/kg for a wood chip stoker. Sampling for carbon monoxide, nitrogen oxides and sulfur oxides was also carried out. A creosote probe was used to determine the tendency of each unit to form creosote in the chimney. At the end of the heating season an examination was made of the type and amount of flue deposits produced by each unit.

Thermal efficiencies of the systems were tested for comparison purposes using an input/output method. The wood fired units showed a high stand-by heat loss which is difficult to apportion correctly to either a direct loss or an indirect house heating gain.

INTRODUCTION

In forested regions of North America, the residential and small commercial space heating market offers an appropriate opportunity to displace oil and gas fuels with wood fuel. The rise of fossil fuel prices relative to wood fuel prices has meant that a greater capital investment can now be justified for a wood fuel combustion system. The Institute of Man and Resources (IMR), an independent research organization in Prince Edward Island, Canada, has concluded a two year demonstration program of advanced wood fired central heating systems. The objectives of the work were to examine the current technology and to determine thermal and emission performance, safety, maintenance and convenience aspects of selected units.

Ten wood fired central heating systems were installed in Island homes and their performance monitored during the heating season of 1979/80. The homes were selected by public draw from 140 applications received from the general public interested in participating in the program. More detail on the equipment, installation and control systems can be found in (1), (7). This paper will concentrate on a description of the systems tested and on the results and conclusions drawn from the demonstration.

EQUIPMENT

A search was carried out in Scandinavia and North America for innovative wood fired central heating systems. In 1978/79, the level of research activity was generally disappointingly low. However small scale technology has a relatively short lead time and currently there is active private sector development of wood fired central heating systems. In Sweden, for example, there are now 22 companies marketing wood chip combustion systems where as in 1978/79 only six were identified (5). In North America there are now three licensees of Professor Hill's innovative heat storage concept of wood heating, determined by IMR as the only novel design found in the original equipment search.

The program contained seven systems which were considered _a priori_ to have innovative features. Three systems representative of conventional designs were included as a control group in the demonstration. Specifications of the systems and the installation site are given in Table 1. Two major features illustrate the differences between the ten systems; one is the type of wood fuel used; and the other is the control method used to regulate the heat output. A summary of these important differences is given below.

CONVENTIONAL SYSTEMS - KERR TITAN, FAWCETT WF200, FRECO C020

These units all use round wood as fuel. Regulation of heat output is achieved by varying the amount of combustion air available. A demand for heat from the house thermostat activates a control motor that opens a primary air vent. When the house thermostat opens, the vent is closed and the fire dies down due to lack of combustion air. The Freco combination boiler has a "swing in" oil burner that fires into the wood combustion fire box. Controls are provided in these systems to ensure that if the wood fire is not controlled by means of the primary air vent, then heat is dumped to the house by switching fans or water circulators. This ensures safe operation by preventing overheating of the furnace or boiler.

ADVANCED SYSTEMS - THERMAL STORAGE

Tarm MB75 - 3675 litre Water Thermal Store

This system uses a high quality wood boiler coupled to a thermal storage system. Round wood fuel is burnt in the boiler at a high combustion rate with a water circulation loop carrying the heat away to the thermal storage.

TABLE 1

SPECIFICATIONS OF COMBUSTION SYSTEMS AND DEMONSTRATION SITE

Advanced Wood Combustion Systems	System Type	Fuel Type	Fuel Feed System	Rated Output (kW_t)	Demonstration House Estimated Heat Loss at -15°C (kW_t)**
Skogma 044 - Hunter Valley F51	Furnace	Chipwood Sawdust	Gravity fed hopper	26	14
Tarm MB75 - 3675 litre Thermal Storage	Boiler	Round Wood	Manual Loading	53	14
Hampton Jetstream 8190 litre Thermal Storage	Boiler	Round Wood	Manual Loading	35	13
Anga & Varme Preheater Stoker - CTC Boiler	Boiler	Chipwood	Preheater screw fed from hopper	18*	14
Anga & Varme Stoker - CTC Boiler	Boiler	Chipwood	Screw fed from hopper	18*	17
Palmia Stoker - Lunenburg Furnace	Furnace	Chipwood	Screw fed from hopper	32	12
Will-Burt S-20 Stoker - 24FA Furnace	Furnace	Pellet Wood	Screw fed from hopper	46	21
Kerr Titan	Boiler	Round Wood	Manual Loading	41	22

(cont'd)

TYPING GUIDE SHEET

122

TABLE 1

SPECIFICATIONS OF COMBUSTION SYSTEMS AND DEMONSTRATION SITE (cont'd)

Advanced Wood Combustion Systems	System Type	Fuel Type	Fuel Feed System	Rated Output (kW_t)	Demonstration House Estimated Heat Loss at -15°C (kW_t)**
Fawcett WF200	Furnace	Round Wood	Manual Loading	35	13
Freco C020	Boiler	Round Wood/Oil	Manual Loading	73	15

* Rated output of CTC Boiler, stoker rated at 50 kW_t maximum.

** Calculated using ASHRAE Heat Loss Method and checked against previous year's oil use and degree day data.

TYPING GUIDE SHEET

Several changes were made at this site from the description given in a previous paper (1). The storage system was finally composed of three 1225 litre fibreglass tanks piped in parallel. A schematic of the system is shown in Figure 1. It should be noted that a water-to-water heat exchanger is used to enable heat to be transferred from the unpressurized water storage system to the pressurized house hydronic distribution system. When the boiler is charged with wood fuel a timer on the furnace controls the circulation pump (P2) in the charging circuit. On burn out of the wood fuel charge the control of the circulation pump reverts to the house thermostat. When the house thermostat calls for heat, both circulation pumps start and heat is transferred from heat storage to the house heating system through the heat exchanger.

Hampton Jetstream - 8190 litre Water Thermal Storage

This system was a prototype of a unit now being produced in Prince Edward Island, based on a concept by Professor Hill (6). The boiler is designed for non-modulating operation and high combustion temperatures. Round wood fuel is used and a combustion air fan ensures turbulent combustion conditions conducive to clean burning. As with the Tarm heat storage system the greatest difficulty during the demonstration was experienced with ensuring a leak free storage system. As shown in Figure 2, nine 910 litre oil tanks were piped in parallel. Insulation was placed around the storage tanks having a value of RSI 3.52 (R-20). At the commencement of the charging cycle, a timer switch is set to the number of hours estimated for the charge of wood to burn. The action of setting the timer switch starts the circulation pump (P2) and reverses the motorized valves at the furnace thus directing the water flow through the furnace. When the timer switch cuts off, the circulation pump stops and the motorized valves return to the rest position. The control of the circulation pump now comes under control of the house thermostat. When the house thermostat calls for heat, both circulating pumps start and heat is transferred from the heat storage to the house heating system through the heat exchanger.

WOOD CHIP COMBUSTION SYSTEMS

Anga & Varme Preheater Stoker and CTC Boiler

Wood chip fuel is loaded into a cylindrical hopper of 0.44 m^3 capacity. Material is transported by means of an auger to a 560 mm diameter preheater or combustion chamber. There, the fuel is burnt on a grate with combustion air blown in as under fire air. The preheater is firebrick lined and insulated. A short gas tunnel, also refractory lined, connects the preheater to the CTC boiler.

The auger is controlled by a two timer system that is manually set. Practical experience with this installation indicated that setting the auger to run 12 seconds "on" and 60 seconds "off" gave good results. If the boiler water temperature reached the high limit setting of the aquastat, then the auger feed was shut down as well as the combustion air fan.

TYPING GUIDE SHEET

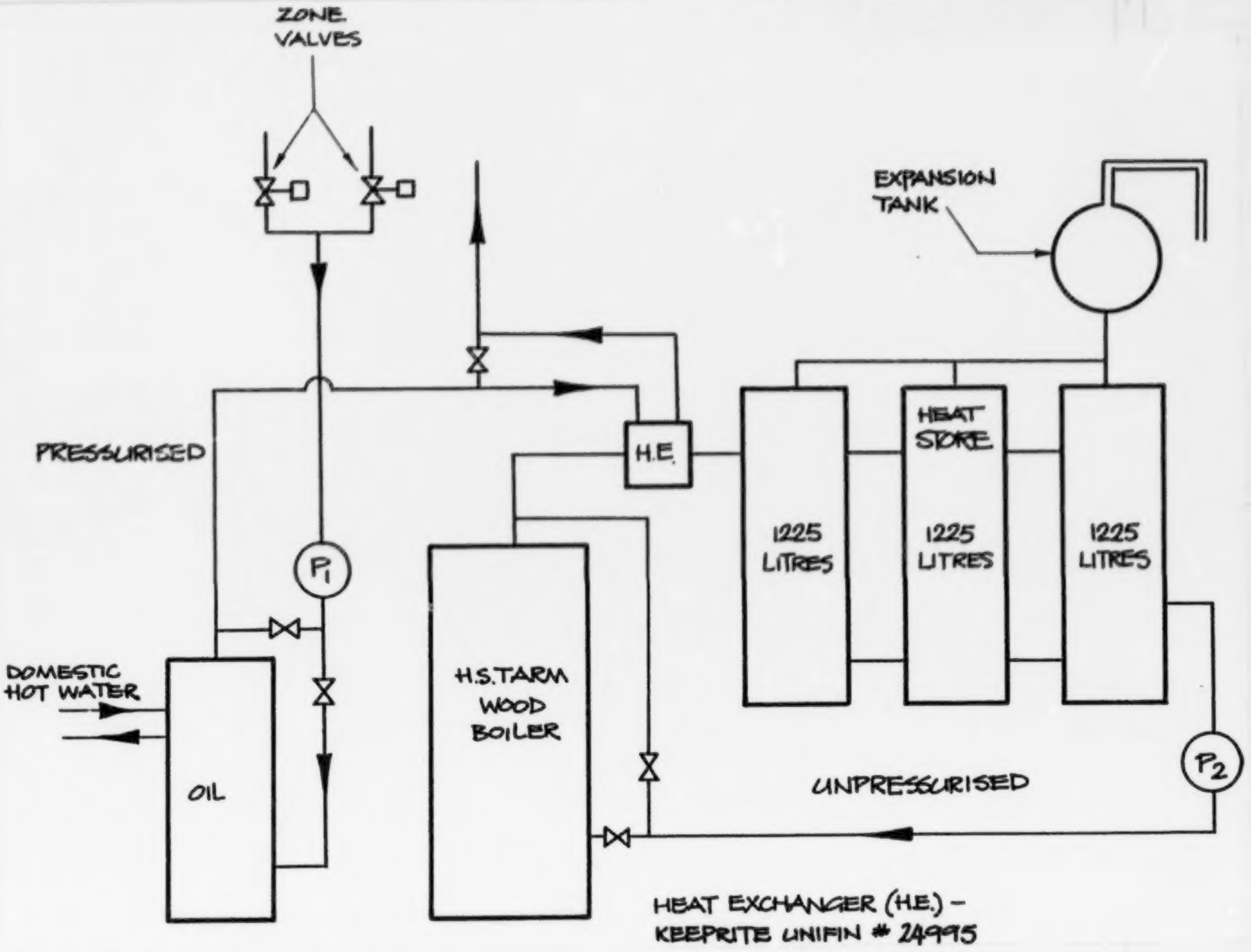

ZONE VALVES
EXPANSION TANK
PRESSURISED
H.E.
HEAT STORE
1225 LITRES
1225 LITRES
1225 LITRES
P1
P2
DOMESTIC HOT WATER
OIL
H.S. TARM WOOD BOILER
UNPRESSURISED
HEAT EXCHANGER (H.E.) - KEEPRITE UNIFIN # 24995

Figure 1. Plumbing Schematic - HS Tarm with Heat Storage

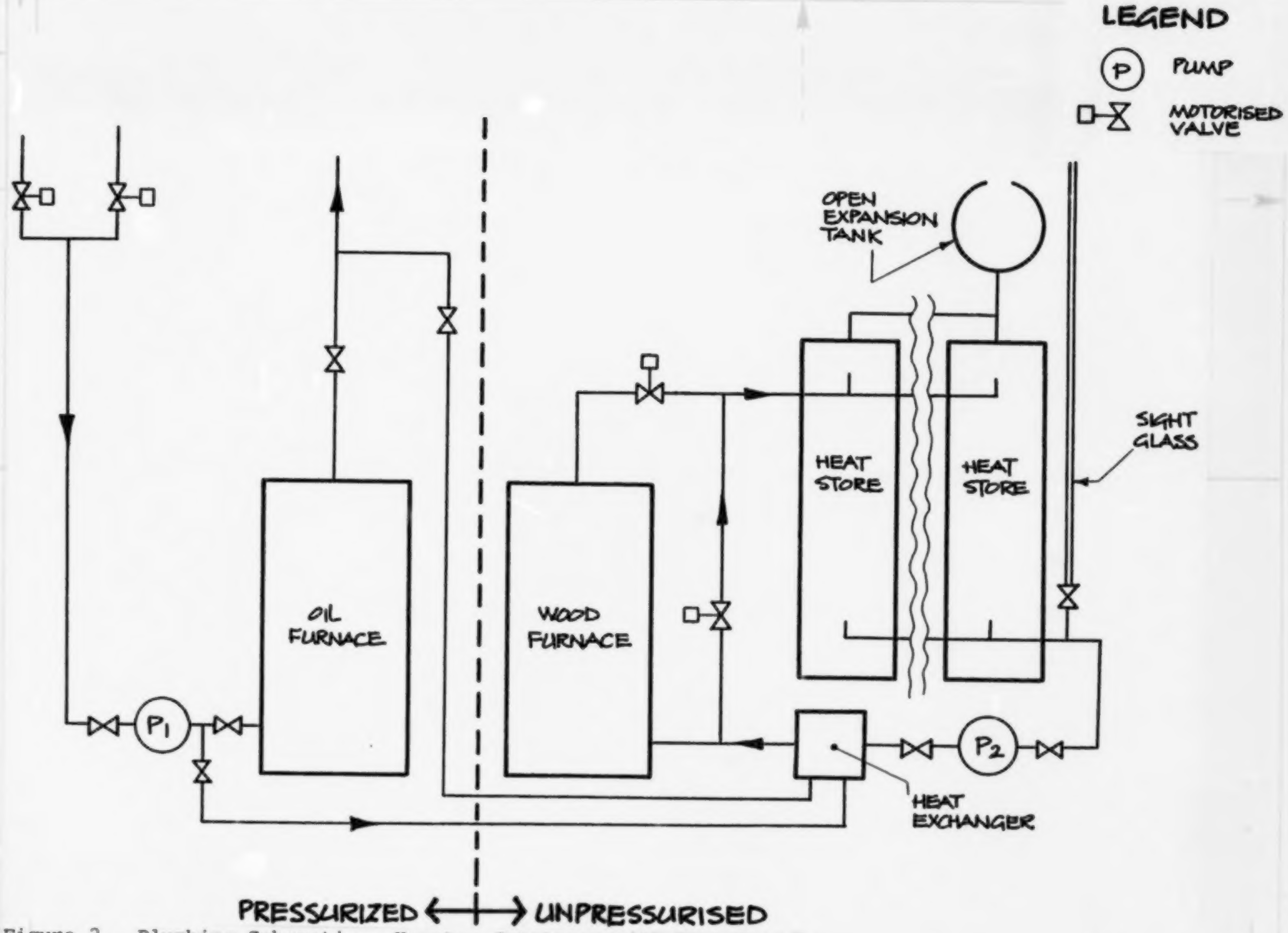

LEGEND
P PUMP
MOTORISED VALVE
OPEN EXPANSION TANK
SIGHT GLASS
HEAT STORE
HEAT STORE
HEAT EXCHANGER
P_2
WOOD FURNACE
OIL FURNACE
P_1
PRESSURIZED ⟷ UNPRESSURISED

Figure 2. Plumbing Schematic - Hampton Jetstream with Heat Storage

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

Anga & Varme Stoker with CTC Boiler

This unit is identical to the preheater stoker except that the wood chip fuel is augered into a retort placed within the fire box of the CTC boiler. Combustion air is blown into the retort and directed through small holes down onto the fuel bed. The control system is the same as described previously.

Skogma 044 Preheater and Hunter Valley Comfort F51

The Skogma 044 is a Swedish gravity fed preheater that was coupled to a Hunter Valley Comfort warm air furnace. A schematic of the system is shown in Figure 3. Control of heat output is achieved by opening or closing the primary under fire air vent on the Skogma. When the house thermostat is open the primary vent on the Skogma is closed and the draft across the unit reduced by opening the air vent in the main furnace. Important components of the Skogma include a refractory tunnel connecting the preheater to the furnace and a stainless steel chip divider placed over the grate. Moisture driven off by the chip fuel passing over the chip divider condenses higher up in the chip storage hopper and prevents a burn back situation. It is important that the hopper be relatively air tight since air leaks would promote burn backs into the hopper.

Palmia Stoker and Lunenburg Warm Air Furnace

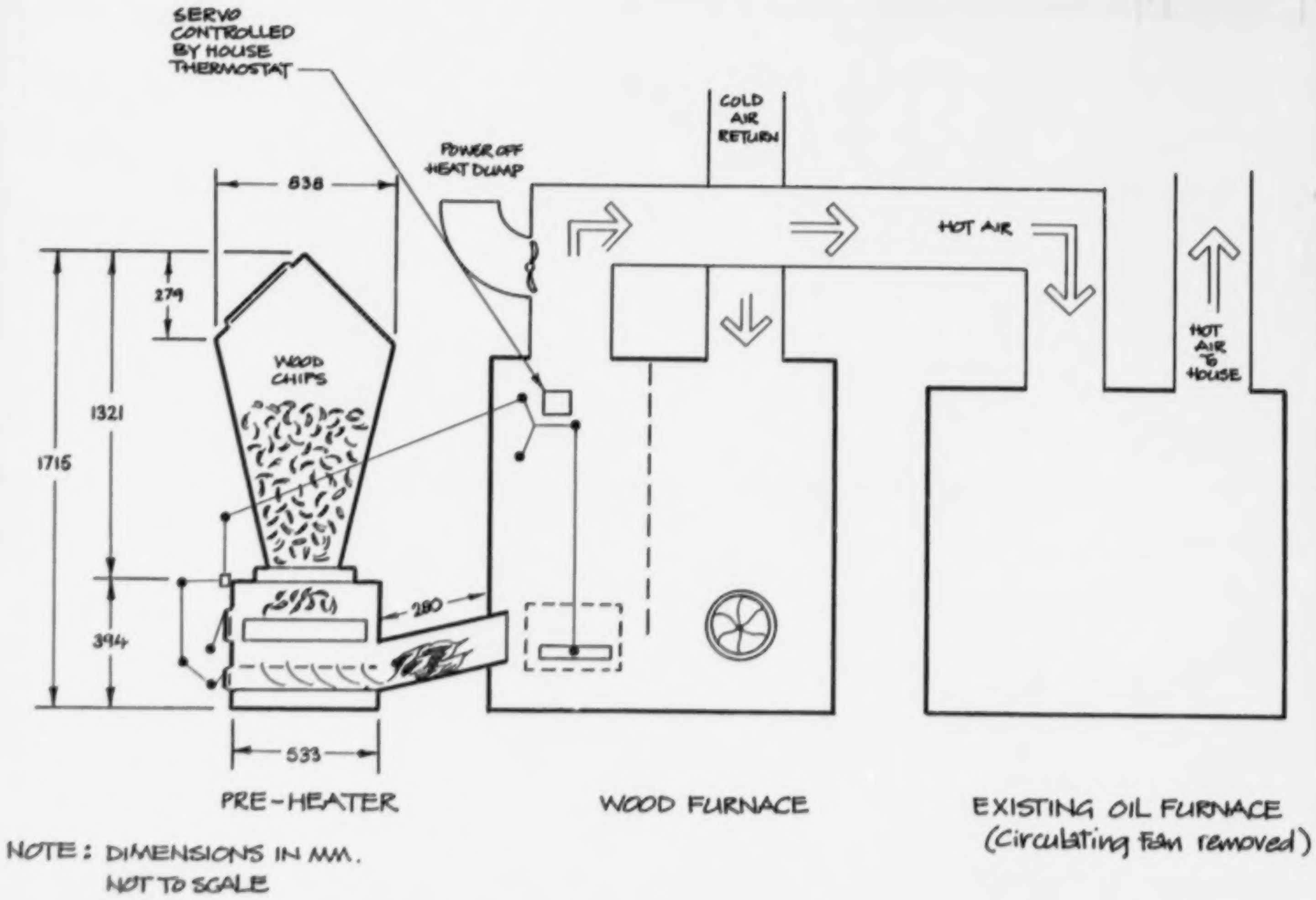
This stoker system consists of an open top hopper of 0.35 m^3 with an auger transporting the material from the bottom of the hopper directly into the warm air furnace. The chip fuel is burnt on a grate under natural draft conditions. Modulation of heat output from this unit is achieved by having the auger run at two speeds. When the house thermostat is not calling for heat the auger turns at a slow rate and the furnace draught vent is closed. When the house thermostat signals a demand for heat output the furnace vent opens and the auger speed is increased. This is not a very effective control system since in the spring and fall the house often overheated. On the other hand, on the coldest days, the system would not provide enough heat.

Will-Burt S-20 Stoker and 24FA Furnace

This system uses pellet fuel which is made by pelletizing dried wood residue such as bark, sawdust or whole tree chips. The stoker furnace is a modified coal stoker with changes made to the pitch of the flight screw. Pellet fuel is screw fed from the hopper which holds approximately 136 kg of material to a retort placed in the combustion chamber of the furnace. Combustion air is blown onto the fuel bed through small tuyeres in the retort. The stoker motor and combustion air fan are controlled by the house thermostat. A "hold-fire" timer can be set so that in mild weather the stoker is run for a few minutes every half hour to maintain a constant, small fire.

FUEL SUPPLY

Those systems using round wood had split and seasoned hardwood delivered by an established fuel wood supply company. Species of wood included maple, beech and birch having a moisture content (MC) ranging from 15-30% (oven dry


SERVO CONTROLLED BY HOUSE THERMOSTAT
POWER OFF HEAT DUMP
COLD AIR RETURN
HOT AIR
HOT AIR TO HOUSE
WOOD CHIPS
838
279
1321
1715
394
280
533
PRE-HEATER
WOOD FURNACE
EXISTING OIL FURNACE
(Circulating Fan removed)

NOTE: DIMENSIONS IN MM.
NOT TO SCALE

Figure 3. Skogma Preheater/Hunter Valley Comfort Wood Furnace Installation

basis).

Wood chip fuel was produced initially by chipping forest residue produced in a cleaning and thinning operation. The wood chip fuel was stored in a grain silo and dried by passing air through the chip mass using the existing grain dryer blower and the perforated floor of the bin. Although no measurements were taken, this method of drying wood chip fuel from 50% to 20-30% MC appears very cost effective and supports the conclusions of similar work (8).

Potato bags containing about 15 kg of wood chips each were filled at the storage site and delivered by truck to the homes in the demonstration. A small bin was constructed outside the house with a chute leading through a basement window. A weekly delivery schedule was required during the winter. Due to water and snow intrusion into the storage, freezing of chips created a problem of fuel hang up in the bins. This problem could be reduced by ensuring that chip fuel storage is weatherproof.

Manual delivery in any large scale operation would appear to be impractical with a fuel having such a low bulk density as fuel wood chips. IMR is currently engaged in demonstrating alternative methods of producing, storing and distributing fuel wood chips for residential use.

For this project pellet wood was acquired from Guaranty Fuels of Independence, Kansas. The pellets are cylindrical, approximately 9 mm in diameter with a length of 10-20 mm. The material was packed in 140 kg drums and delivered to the site by truck.

An advantage of the processed wood fuel over wood chip fuel is the decrease in fuel storage volume required in the home. Some characteristics of the wood fuels used are presented in Table 2 together with the energy density of thermal storage.

EXPERIMENTAL PROGRAM

It was recognised from the outset that the type and quality of data to be sought during the demonstration were different from that which would be obtained in laboratory testing. A decision was made to use simple instrumentation where possible and to ask the homeowners to participate in the data acquisition. The areas in which data were sought included:

i) thermal performance
ii) emission performance.

THERMAL PERFORMANCE

A house central heating system is installed to provide space heat to the living space of a dwelling. How effectively it converts fuel to warm the living space is a measure of its thermal performance. The instantaneous measurement of thermal performance of a wood heating system is not a simple procedure due, among other factors, to the inability to measure easily the fuel consumption rate, and the possibility that fuel moisture content and hence heating value can vary during a test. An input/output method of determining thermal performance over a number of days was therefore selected for the

TABLE 2

ENERGY DENSITY OF WATER THERMAL STORAGE, WOOD AND OIL FUELS

Fuel Type	Bulk Density kg/m^3	Lower Heating Value KJ/g	Energy Density GJ/m^3
18% MC Round Wood	310	14.8	4.6
30% MC Wood Chips	230*	12.8	2.9
8% Wood Pellets	600	15.6	9.4
Water Thermal Storage $\Delta T = 40°C$			0.16
#2 Fuel Oil			37

*Bulk density for spruce chips taken from Beijbom, L. and Martin Nilsson, Fliseldning for Gardar och Smahus (Chip Heating of Farms and Single Family Homes), Silviconsult Ltd., Bjarred, Sweden, 1979.

TYPING GUIDE SHEET

demonstration. The ratio of the useful heat delivered to the potential heat value of the wood fuel used by a system yields the thermal efficiency of that system.

A logbook was kept at each house and the homeowner was asked to record the mass of wood as he or she charged the furnace. Household scales were used with a calibrated accuracy of ±2%. Moisture content of the fuel was determined using a calibrated Delmhorst Model RC-1 probe meter. Spot measurements were made at the sites by the project consultant for the moisture content of the fuel but it proved difficult to determine the overall error in the fuel heating value due to this method. In order to compensate for this, a test period over the winter was selected for each site during which the equipment operated consistently and adequate fuel use data were obtained.

The thermal output from the boiler systems was obtained using a heat flow meter placed in the hydronic distribution lines. The ISTA meter consists of a turbine flow meter and two temperature sensors placed in the out flow and return hot water lines. The thermal energy delivered to the house is computed by the device and shown in kWhs. These meters are normally used in Europe to meter district heating systems. The heat output from the warm air furnaces was metered using the same principle. Two thermocouples of type E were installed; one in the warm air plenum, and one in the return duct. A temperature difference between the two thermocouples generated an emf that, over the small temperature difference of interest, could be assumed to be linear. The millivolt signal generated was integrated using a portable millivolt integrator from Delta T Devices, Cambridge, UK. The air mass flow was measured in the distribution duct and a timer placed on the fan motor. The elapsed time indicated by the timer gave total air mass flow in any period of time. The average temperature through which this air mass was raised could be obtained from the reading on the integrator.

From instrument specifications it is estimated that the error in measuring heat output from the boiler units was ±1% and for the warm air systems the error is estimated to be ±3%. Some systems supplied domestic hot water to the home. This energy output was monitored by placing a water meter in the well water line and measuring the inlet and outlet water temperatures during a special test period. The results of the test program are shown in Table 3.

Discussion

The input/output efficiencies of the wood burning systems did not exceed 50%. This is a conservative measure of their true performance since a proportion of stand-by losses can be credited to heating the living space. Note that the Freco wood/oil combination when using oil delivered 44% overall efficiency on an input/output basis. It should be stressed that the performance of wood burning systems, especially the round wood units, is significantly affected by factors not related to the combustion system design. The input/output efficiency method used allows determination of average performance in the field that would be very complex to achieve using a stack loss method. Although the efficiencies may be low, they do allow for some cautious comparative analysis.

TABLE 3

OVERALL INPUT/OUTPUT EFFICIENCIES

TYPE OF UNIT	UNIT	FUEL TYPE	TEST PERIOD	NUMBER OF DAYS IN TEST PERIOD	DEGREE DAYS IN TEST PERIOD BELOW 18°C (°C-DAYS)	MASS OF FUEL BURNED IN TEST PERIOD (Kg)	AVERAGE MOISTURE CONTENT OF FUEL BY WEIGHT (%)	LOWER HEATING VALUE (Kj/Kg)	TOTAL ENERGY AVAILABLE (Gj)	ENERGY SUPPLIED TO HOUSE HEATING SYSTEM (Gj)	ENERGY SUPPLIED TO D.H.W. (Gj)	OVERALL INPUT/OUTPUT EFFICIENCY (%)
CONVENTIONAL UNITS	KERR-TITAN	ROUND WOOD	14 MAR. 80 to 8 APR. 80	26	489.7	1408	30					*
	FAWCETT WF200	ROUND WOOD	22 FEB. 80 to 15 APR. 80	54	1,121.0	1,672	14	15,650	26.7	12.33		47
	FRECO CO20	ROUND WOOD	15 MAR. 80 to 27 MAR. 80	13	256.7	760	18	14,800	11.25	3.40	0.62	36
	FRECO CO20	OIL	28 MAR. 80 to 1 MAY 80	35	490.6	371.5 Litres (OIL)		37,170 Kj/Litre	13.81	4.79	1.27	44
HEAT STORAGE UNITS	TARM MB75	ROUND WOOD	22 MAR. 80 to 6 APR. 80	16	271.2	334	14					**
	HAMPTON JETSTREAM	ROUND WOOD	8 FEB. 80 to 19 FEB. 80	72	1,553.9	2,896	17	15,010	43.47	16.83		39
PELLET BURNER	WILL-BURT	WOOD PELLETS	26 FEB. 80 to 24 APR. 80	58	1,142.1	3,443	8.1	15,570	53.61	24.86		46
CHIP BURNERS	ANGA VARME STOKER/PREHEATER -CTC BOILER	WOOD CHIPS	17 MAR 80 to 1 MAY 80	20	247.2	1,388	30	12,790	17.75	7.14		40
	ANGA VARME STOKER -CTC BOILER	WOOD CHIPS	29 FEB 80 to 24 APR. 80	39	676.9	4,548	32	12,350	56.16	21.01		37
	SKOGMA PREHEATER-VALLEY COMFORT	WOOD CHIPS	30 JAN. 80 to 14 MAR. 80	45	1,183.3	3,968	32	12,350	49.00	11.86	1.70	28
	SKOGMA PREHEATER-VALLEY COMFORT	SAWDUST	31 MAR. 80 to 13 APR. 80	14	208.7	937	49	8,560	8.02	1.16	.53	21
	PALMIA STOKER LUNENBURG F-51	WOOD CHIPS	15 FEB. 80 to 3 APR. 80	44	1,129.3	3,153	35	11,680	36.82	14.38		39

*Faulty kWh meter during test.

**Storage tank now insulated - inadequate data.

TYPING GUIDE SHEET

It is felt that the loss figures obtained for the Skogma 044 were due to a high jacket loss from the preheater body. The homeowner commented that his basement and floors had never been as warm. Since this was a well insulated basement this is a case in which the stand-by loss contributed significantly to the house heating demand.

From a performance aspect the conventional units appeared comparable to the more advanced units. In the case of the Fawcett it is felt that the careful maintenance of this unit by the homeowner contributed significantly to the performance. The lady of the house who regularly stoked this unit reported that when her husband took over the duties, the house either overheated or the fire went out.

The lower than expected performance of the Jetstream heat storage system can be attributed to long uninsulated pipe runs in the basement. It is important that the system design of the thermal storage units be carefully considered. The installation of this prototype unit proved to be a valuable experience.

The relatively high efficiency of the Will-Burt unit is felt to be due to the good combustion efficiency of wood pellet combustion and the low stand-by loss of the maintenance fire.

The Tarm MB75/heat storage system and the Kerr Titan did not provide adequate data during the program to determine input/output efficiencies. The Tarm did not have enough running time and the Kerr Titan suffered a defective thermal kWh meter.

Seasonal Performance

In Table 4 the difference in input/output efficiency is shown between winter and spring operation. The efficiencies show an expected decline in the spring except for the Fawcett unit. The explanation was found when the homeowner was questioned. In the spring the unit was lit in the morning and allowed to burn out. Therefore, in contrast to the other units, the Fawcett did not operate at any time in the spring period in a stand-by mode. In general the lower duty cycle in the spring period costs about 10-15% in measured input/output efficiency.

Conclusions

The input/output method proved useful in characterizing the "as fired" performance of the systems. An improvement would have been to have switched to oil heating for a test period during the heating season. Assuming no change in the homeowner's living habits, the amount of oil used, the input/output and spot efficiencies obtained, together with the test period degree days, would have been a useful addition to the data. The main conclusion appears to be that the conventional systems, if carefully operated, are comparable in performance to the more automated systems.

TABLE 4

SEASONAL EFFICIENCY

TYPE OF UNIT	UNIT	FUEL TYPE	WINTER PERIOD				SPRING PERIOD			
			TEST PERIOD	TOTAL AVAILABLE ENERGY (MJ)	ENERGY SUPPLIED TO HOUSE (MJ)	OVERALL EFFICIENCY (%)	TEST PERIOD	TOTAL AVAILABLE ENERGY (MJ)	ENERGY SUPPLIED TO HOUSE (MJ)	OVERALL EFFICIENCY (%)
CONVENTIONAL UNITS	KERR-TITAN	ROUND WOOD	*							
	FAWCETT WF 200	ROUND WOOD	28 FEB. 80 to 11 MAR. 80	7,487	3,077	41	24 APR. 80 to 29 APR. 80	648	363	56
	FRECO 6020	ROUND WOOD	**							
	FRECO 6020	OIL								
HEAT STORAGE UNITS	TARM MB 75	ROUND WOOD	***							
	HAMPTON JETSTREAM	ROUND WOOD	8 FEB. 80 to 22 MAR. 80	31,671	13,225	42	22 MAR. 80 to 19 APR. 80	11,798	3,602	31
PELLET BURNER	WILL-BURT	WOOD PELLETS	28 FEB. 80 to 11 MAR. 80	15,216	7,165	47	17 APR. 80 to 24 APR. 80	4,600	1,468	32
CHIP BURNERS	ANGA VARME STOKER/PREHEATER -CTC BOILER	WOOD CHIPS	17 MAR. 80 to 19 MAR. 80	2,293	1,130	49	26 APR. 80 to 30 APR. 80	2,793	1,105	40
	ANGA VARME STOKER-CTC BOILER	WOOD CHIPS	29 FEB. 80 to 24 MAR. 80	18,232	8,942	49	24 MAR. 80 to 28 APR. 80	34,460	12,067	35
	SKOGMA PREHEATER - VALLEY COMFORT	WOOD CHIPS	30 JAN. 80 to 6 FEB. 80	8,701	2,082	24	20 APR. 80 to 28 APR. 80	9,487	1,626	17
	SKOGMA PREHEATER-VALLEY COMFORT	SAWDUST								
	PALMIA STOKER - LUNENBURG F-51	WOOD CHIPS	16 FEB. 80 to 23 FEB. 80	6,418	2,892	45	28 MAR. 80 to 1 APR. 80	3,530	251	7

*Meter not operating.
**Insufficient data.
***Storage tanks not insulated - insufficient data.

EMISSION PERFORMANCE

Concern has been expressed in recent years with regard to the level and nature of the products of wood combustion (4). Two areas of concern can be identified.

The first is that particulates, carbon monoxide, and organic material from wood combustion systems will adversely affect environmental air quality. The second concern is that organic material will condense on flue surfaces and lead to creosote formation and creation of a fire hazard.

It was decided to address the first concern by sampling the wood smoke emissions at the chimney exit; in effect, considering the combustion device and its chimney as a single system. Monitoring creosote build up in the site chimneys using two separate methods was also done during the program.

Measurement of Emission Factors

It was decided to obtain emission factors for particulates, carbon monoxide, nitrogen oxides and sulfur oxides during operation of each of the ten units.

Particulates--A high volume sampling method was undertaken, similar to that used by Butcher (3). A 1.07 m aluminum cone was positioned over the chimney in such a way as to minimize the effect of the high volume sampling in the furnace operation. The smoke gases were sucked through the cone through a 203 mm x 254 mm glass fibre filter having a retention size of 0.3 microns. The sampling volume rate started out at $3.1 m^3$/min. and decreased as the filter loaded up. The sample times for each filter ranged from 15 seconds to 10 minutes depending on the quantity of emissions from the chimney. During a test, several tens of filters were used; the changes were made as expeditiously as possible. The pre-weighed filters were then stored in air-tight containers until they were dried and re-weighed.

Selected filters were extracted with 150 ml of benzene in a Soxhlet extractor for 24 hours. The solvent was then evaporated and the extract desiccated to constant weight at room temperature and weighed. This fraction was determined to consist of the condensable organics in the filter sample. The full test procedure and methodology are reported in (7), (9).

Carbon Monoxide--Carbon monoxide was continuously monitored using an infrared analyzer, and spot monitored using a gas chromatograph. The sampling port was located in the smoke pipe leading from the furnace to the chimney flue. The flue gas velocity and, hence, volume flow were determined using a pitot tube method. Two traverses of six points each were taken to determine flow velocity profiles in the smoke pipe. During the test program, the pitot tube was mounted in the centre of the smoke pipe.

Nitrogen Oxides, Sulfur Oxides--Spot samples were taken using Gastec and Drager gas monitoring tubes.

The test period was normally two or three hours. An attempt was made to maintain a consistent operating cycle. From a cold condition the unit was allowed to burn at maximum power for an hour. Then control was returned to the house thermostat to allow cycling conditions for an hour. The final period was at a stand-by or a low output condition. The average emission factors obtained during the test program are shown in Table 5.

The most satisfactory units with respect to environmental emissions appeared to be the Will-Burt, Skogma and Anga & Varme Preheater. The Jetstream prototype was satisfactory except for high carbon monoxide emissions. It is understood that further development has significantly reduced this figure. A comparison with emission data for other fuels taken from (2) is given in Table 6.

Creosote Formation

To determine the build up of creosote formation in chimney flues small flat steel plates (115 mm x 130 mm) were inserted in the smoke pipe with the exposed surfaces parallel to the flue gas flow. The probe was mounted 0.5 m from the smoke exit on the furnace and boiler. Close proximity to bends in the smoke pipe were avoided. The rationale for this test procedure was that creosote build up would occur on the probe and if the weight of the probe when clean was known, the mass of creosote build up after a known period of time could be easily determined. It was decided that the results from this test should be treated qualitatively rather than quantitatively. This was due to the large number of variables such as flue gas velocity, placement variations of the probe, and influence of exposure time. The results are shown in Table 7.

With the exception of the Freco, the sites all commenced the heating season with new or swept chimneys. At the end of the program the flues were swept and the mass of material recovered from the flue established. Its heating value was also determined. A deposition rate was calculated from the mass normalized with respect to the chimney length. This calculation yields a flue deposition rate kg ash/(kg fuel . chimney length in metres) that agrees reasonably well in ranking with the creosote probe data. Low build up of deposits on the creosote probes of units such as the Jetstream and Will-Burt give also low flue deposits which had a low heating value.

An exception is the Anga & Varme Preheater where a heavy deposit was obtained on the probe although the flue yielded only a small amount of material. The reverse was true with the companion Anga & Varme unit. No suitable explanation for this can be proposed.

Conclusions

Certain units in the test program operated at much higher levels of combustion efficiency than others. Design features that contributed to this are felt to be:

i) refractory lined combustion chambers
ii) forced combustion air
iii) fuel feed systems.

TABLE 5

AVERAGE EMISSION FACTORS MEASURED AT CHIMNEY EXIT

Wood Burning Device	Wood Type Moisture Content ( )	Particulate Matter g/kg	Condensable Organics g/kg	Carbon Monoxide g/kg	Nitrogen Oxide g/kg	Sulfur Dioxide g/kg
Will-Burt	Compressed Wood Pellets (8%)	0.72	.18	0.9	3.17	.27
Skogma	Sawdust (43%)	0.63	.19	6.6	.41	.42
Palmia	Wood Chips (27.4%)	38.60	12.59	66.42	.70	.65
Anga & Varme (Preheater)	Wood Chips (23.3%)	1.12	.25	6.5	.32	.11
Anga & Varme	Wood Chips (6%)	5.02	.66	72.37	.62	.10
Jetstream/ Storage	Beech (15.2%)	1.09	.30	59.4	.43	.61
	Beech (21.0%)	0.99	.22	94.9		
	Beech (15.7%)	0.94	.26	52.8		
	DBF (5.6%)	2.61	.81	112.8		
	Maple (35.4%)	1.01	.20	68.9		
HS Tarm/ Storage	Beech & Maple (13.9%)	1.72	.41	39.6	.46	.67
	Maple (28.8%)	0.83	.22	72.5		
	DBF (5.6%)	1.13	.20	23.0		
Kerr Titan	Beech & Maple (21.6%)	4.86	1.32	83.7	.16	.81
	DBF (5.6%)	3.78	.93	93.9		
	Beech & Maple (30.0%)	2.89	.65	161.9		
Fawcett WF200	Birch & Maple (13.7%)	4.26	1.80	54.9	.47	.16
	DBF (5.6%)	2.71	1.11	33.6		
	Birch & Maple (14.1%)	3.52	1.80	99.2		
Freco C020	Birch & Maple (17.4%)	7.58	1.84	21.9	.17	.14
	DBF (5.6%)	4.12	.91	23.3		

TABLE 6

EMISSION FACTORS OF RESIDENTIAL HEATING SYSTEMS
gm/GJ

	Particulates	Hydrocarbons	CO
Coal*	331	331	1488
Oil*	6.0	4.3	17.2
Gas*	2.2 - 6.5	4.3	8.6
Will-Burt	40	10	50
Skogma	60	20	630
Jetstream	69	15	6636

* Figures taken from (2).

EPA Form 2200-4 (4-80)
TYPING GUIDE SHEET

TABLE 7

CREOSOTE FORMATION - SUMMARY OF RESULTS

Creosote Probe				Chimney Deposits				
Unit	Probe Deposit	Nature of Deposit	Days Probe in Flue	Chimney Length (m)	Mass of Material Removed From Flue (kg)	Estimated Mass of Wood Burned (kg)	Deposition Rate (kg/kg.m) x 10^{-6}	Higher Heating Value of Flue Deposit (KJ/kg)
Kerr Titan	Medium*	Black Tar	66	12	6.0	12,000	42	21,720
Fawcett	Very Heavy	Black Sticky Tar	35	5	4.3	6,000	143	23,300
Freco	Very Heavy	Black Sticky Tar	48	5	12.7	2,700	940	17,470
Tarm	Heavy	Black Tar	39	7	1.1	1,800	87	5,400
Jetstream	Light	Light Grey Ash	50	5	>0.1	3,000	7	2,430
Will-Burt	Light	Light Grey Ash	23	6	2.1	11,000	32	3,670
Anga & Varme with Preheater	Heavy	Black Sticky Powder	37	9.4	0.7	6,000	12	4,270
Anga & Varme	Medium	Black Tar	35	7.3	5.8	7,000	114	10,060
Skogma	Light	Black Tar	27	5	0.7	10,000	14	12,090
Palmia	Medium	Black Sticky Tar	36	5	0.4**	3,700	22	15,410**

*The flue pipe was made too small and a quantity of the deposit was lost on removal.
**After chimney fire.

Those units having lower levels of particulate and carbon monoxide stack emissions tended to have fewer chimney deposits and hence a reduced chance of flue fires. It is concluded that, with increased development activity, all three forms of wood fuel - chips, pellets, cordwood - can be used in central heating systems with an acceptable level of emissions.

OVERALL DEMONSTRATION CONCLUSIONS

The program provided an opportunity to evaluate a number of interesting wood fired central heating systems in residential homes. It is concluded that increased sophistication in design can lead to an increase in convenience of use, lower levels of pollution, and reduced maintenance requirements. The conventional design of furnace or boiler can give adequate thermal performance provided that the homeowner is willing to give a high level of supervision and maintenance to the system.

With round wood combustion the heat storage concept appears to offer a route to efficient, clean and convenient central heating systems. It is essential that the importance of the system design aspect of thermal storage systems be recognised. A poor tank and control design can degrade the thermal performance of the whole system to a significant extent.

Using chip or pellet fuel offers the possibility of modulating fuel feed to meet the thermal demand of the house. A problem area with wood chip fuel is its low energy density and the desirability of covered storage. Fuel wood storage and delivery systems require some innovative research to complement new furnace concepts. Pneumatic delivery of pellet fuel is the subject of an IMR demonstration program to determine the costs of such a wood fuel delivery system. Delivery by bags may also be practical in urban areas for small volume use.

The stoker systems need to be refined so that the cost/unit can be reduced. A major problem at present is that with processed fuel the available capital for the combustion unit is reduced due to significant wood fuel costs. The small commercial market may be easier to penetrate initially with convenient and clean burning systems.

More work is required to determine the relationship between efficiency testing on an input/output basis and using a stack loss method. Stand-by losses from wood combustion systems can be significant and should be reduced in new designs.

ACKNOWLEDGEMENTS

The author wishes to thank all those at Island Energy Associates who were engaged in this project namely Art Wright, Roger Wright and Dennis Edell. Appreciation is also extended to the emission testing team at Atlantic Analytical, Alex Graham, John Synnott and Stephen Miller. The assistance of Martha Musgrove in the review and Gail Carmody in the typing of this report is much appreciated. Funding for this project was provided by the Canada-P.E.I. Agreement on Renewable Energy Development.

REFERENCES CITED

(1) Brandon, R.J., *Residential Wood Fired Furnaces: A Demonstration of Advanced Systems*, Institute for Gas Technology, "Energy from Biomass and Wastes IV" Symposium, Florida, January 1980.

(2) U.S. EPA, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, 3rd Ed., NTIS PB 275 525.

(3) Butcher, S. and E.M. Sorenson, *A Study of Wood Stove Particulate Emissions*, Air Pollution Control Association, 29:724, 1979.

(4) Cooper, J.A., *Environmental Impact of Residential Wood Combustion*, Wood Energy Institute, "Wood Heating Seminar 6", Georgia, February 1980.

(5) Fridolph, B., Anga & Varme AB, Sweden. Private Communication, September 1980.

(6) Hill, R.C., *Stick Wood Research at the University of Maine at Orono*, Wood Energy Institute, "Wood Heating Seminar 5", Missouri, September 1979.

(7) Island Energy Associates, *Wood Fired Residential Heating Demonstration: Final Report*, The Institute of Man and Resources, August 1980.

(8) Johansson, K.J., *Torking Av Bjork Til Brenselformal* (Drying of Birch for Fuel), Norsk Institutt for Skogforskning, Rapp 6/79, ISBN-82-7169-227-5.

(9) Synnott, J.A., *A Study of Emissions from Residential Wood Combustion Furnaces*, for presentation at the 74th Annual Air Pollution Control Association, Philadelphia, June 1981.

EPA Form 2350-6 (6-80)

TYPING GUIDE SHEET

RESULTS OF LABORATORY TESTS ON WOOD-STOVE EMISSIONS AND EFFICIENCY

by

B. R. Hubble

and

J. B. L. Harkness

Energy and Environmental Systems Division

Argonne National Laboratory

Argonne, Illinois 60439

Invited paper to EPA-conducted conference on Wood Combustion Environmental Assessment held in cooperation with the Wood Heating Alliance 1981 International Trade Show and Wood Heating Seminar, New Orleans, Louisiana, February 21-24, 1981.

RESULTS OF LABORATORY TESTS ON WOOD-STOVE EMISSIONS AND EFFICIENCY*

by

B. R. Hubble

J. B. L. Harkness

Energy and Environmental Systems Division
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

Air-tight, wood-burning stoves were operated in a manner consistent with typical residential heating requirements in order to determine particulate and carbon monoxide emissions and creosote build-up. Test data are presented as functions of burn-rates and stove efficiencies.

The principal conclusions are that emissions from the stove used in this study are related to log-size and wood burn-rate and that CO and particulate emissions and creosote build-up increased with increasing efficiency of operation. Therefore, future environmental testing should be conducted at typical stove operating conditions, low burn-rates with large logs.

In addition, heat-loss calculations show a trade-off between sensible heat loss and CO-fuel heat loss over the range of burn-rates studied. This indicates that, if further improvements in stove efficiencies are desired, improvements in stove combustion efficiency are needed. This also decreases stove emissions.

---

* The emissions testing reported here was sponsored by the United States Department of Energy. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the United States Government. Argonne National Laboratory operates as a contractor to the Department of Energy; as such, the findings of this report do not necessarily reflect

Department of Energy policy. The efficiency calculations reported in this paper are based on data obtained during the course of the emissions testing program. Although these calculations constitute a straightforward development of the information obtained in testing, they go beyond the scope of the program as sponsored by the United States Department of Energy and were not solicited by the sponsor.

INTRODUCTION

Wood has become increasingly prominent as a fuel source for residential heating; at the same time, there has been growing concern over the potential environmental impacts associated with the use of wood for this purpose[1-5]. The favorable system thermal efficiencies achieved by air-tight stoves as contrasted to fireplaces have made these types of wood-burning appliances particularly attractive.

In view of these facts, we believe the results from a DOE/Biomass Energy Systems Division funded experimental research program at ANL will be of interest. Our research effort has two main objectives, namely:

(1) to characterize the emissions from generic types of residential stove units, and

(2) to categorize the emissions as a function of typical stove user conditions.

The results of the program will be used to project community air-quality impacts, assess implications for health effects, and determine if system design and operation trade-offs exist relevant to the quantity and nature of environmental emissions.

We here present our results from the testing of one generic type of air-tight stove (horizontally baffled, updraft). Although it was not a goal of this program to do so, we also have correlated our emission results with calculated estimates of the stove efficiencies.

Wood stoves are used either as supplemental space heaters or as the sole source of heat supply for a home. Heat-output requirements will vary greatly depending on the home size and design, the level of insulation, and the site/climate. The results reported by Hayden et al.[6-8] on a study of homes in Ottawa, Canada, provide an example of heat-output requirements for a fairly cold climate--2390 to 4780 kcal/hr. This range suggests that for a wood stove using a hardwood such as dry red oak, with a higher heating value near 4780 kcal/kg, the required burn rate to heat a home would fall in the 0.5 to 1.0 kg/hr range. Even doubling this range to account for energy losses resulting from the moisture content of the wood and the inherently limited thermal efficiences of wood stoves, we still find that the heat-output requirements dictate relatively low burn rates. Moreover, these comparatively low burn rates would be utilized a significant fraction of the time, because overnight operation is biased by the need to maintain a fire.

The primary operational parameters available to homeowners to control the burn rate are the combustion-air-inlet control (opening) and the log size. Accordingly, the emissions measurements were characterized using combustion-air-inlet setting and log size as operator variables.

4

EXPERIMENTAL APPROACH

The experimental approach employed in our program, is diagrammed schematically in Fig. 1. The air-tight, horizontally baffled stove is positioned on an electronic scale to measure mass changes and thus obtain burn-rate information. The stove used in these experiments, which is commercially available, is constructed of cast iron, has dimensions of 0.68 m x 0.47 m x 0.66 m, and weighs approximately 100 kg. It has been modified by the addition of six thermocouples, positioned near the center of the firebox above and below the baffle plate, to monitor fire-box temperatures. The stove was alleged to have both primary and secondary air-inlet control; however, upon disassembling the door, it became apparent that both the primary and secondary air enter the firebox at a common point.

This stove uses a 0.13-m-diameter flue pipe, which in our experimental arrangement (see Fig. 1) passes inside a 0.20-m-diameter flue pipe in such a manner that no mechanical connection exists between the two pipes. This arrangement isolates the stove and sampling system for the mass measurements. (Galvanized 30-gauge flue pipe was used in all the experiments.) Smoke is carried out of the laboratory by the 0.20-m-diameter pipe and is finally vented upward approximately 10 m before being released into the surrounding atmosphere.

Stack-gas sampling occurs 2.34 m above floor level (1.94 m above the center of the chimney outlet, which is at the back of the stove). The sample is withdrawn at the center of the flue pipe by a 0.013 m-diameter stainless-steel sampling nozzle. Not shown in Fig. 1 are a thermocouple, a velocity probe, and a second sample line; these are located as near the sample probe as possible. The second sample line goes to non-dispersive infrared (NDIR) instruments for CO and CO_2 measurements.

The flue-gas sample train itself can be described as a "modified" EPA method-5 sample train, in which particulate, condensible, and gaseous samples are separated out and collected. The stack-gas sample, which we seek to remove isokinetically* and isothermally, is first passed through a cascade impactor (Anderson 2000, Inc., Mark II--Atlanta, Georgia) to remove the particulate sample and classify it by size. Both the sample probe and the cascade impactor are kept at the measured stack temperature to prevent condensation of gaseous species or volatilization of species condensed within the chimney. Materials collected by the impactor are defined to be the particulate matter.

After passing through the cascade impactor, the stack gas is then cooled and pulled through a series of three cold traps, the first of which is held at 0°C and the last two at -20°C, where the samples here referred to as "condensibles" are removed from the stack gas. These samples also contain the H_2O vapor in the stack gas; consequently, separation of the

---

* The goal of isokinetic sampling was not achieved in this study, because the observed stack-gas velocities were so low that commercially available velocity instruments either were not applicable (e.g., pilot tube) or not adaptable (e.g., hot-wire anemometer).

.146

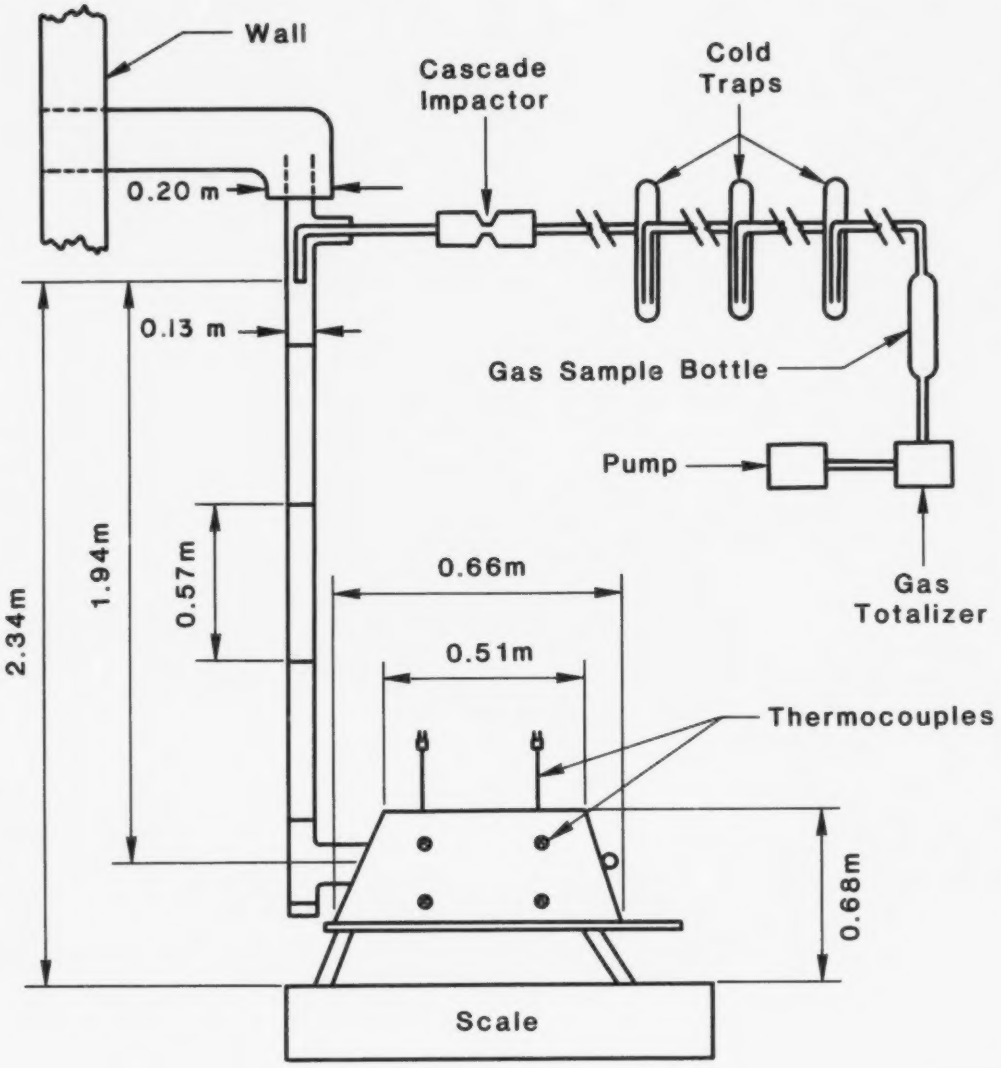

Wall
Cascade Impactor
Cold Traps
0.20 m
0.13 m
Gas Sample Bottle
Pump
Gas Totalizer
2.34m
1.94m
0.57m
0.66m
0.51m
Thermocouples
0.68m
Scale

Fig. 1 Schematic Diagram of Experimental Apparatus Employed to Measure Environmental Emissions.

TYPING GUIDE SHEET

water from these samples is required before determining the concentration of the organic condensibles. Results of these determinations will be reported at a later date.

Gas samples are then removed before the stack gas goes through a gas meter for a total sample-gas volume measurement. These "grab" samples have been analyzed using mass spectroscopy.

Collection of one other type of sample, creosote, is illustrated in Fig. 1. Creosote is the material that collects and builds up on the walls of the flue pipe. Before each experiment, three new (un-used) 0.57-m-long sections of flue pipe, as well as the tee section and bottom cap, were throughly cleaned and dryed. These chimney components, weighed before and after each experiment, provide a measure of the creosote build-up. Creosote collection was terminated before a fire died out by physically removing these five chimney sections. The creosote samples then were retrieved from the flue-pipe sections.

At present we are characterizing collected solid- and liquid-phase samples (particulates, creosote, and condensibles) through chemical analysis, primarily employing the analytical techniques of high-performance liquid chromatography (HPLC) and gas chromatography/mass spectroscopy (GC/MS). Results of these analyses will be reported at a later date.

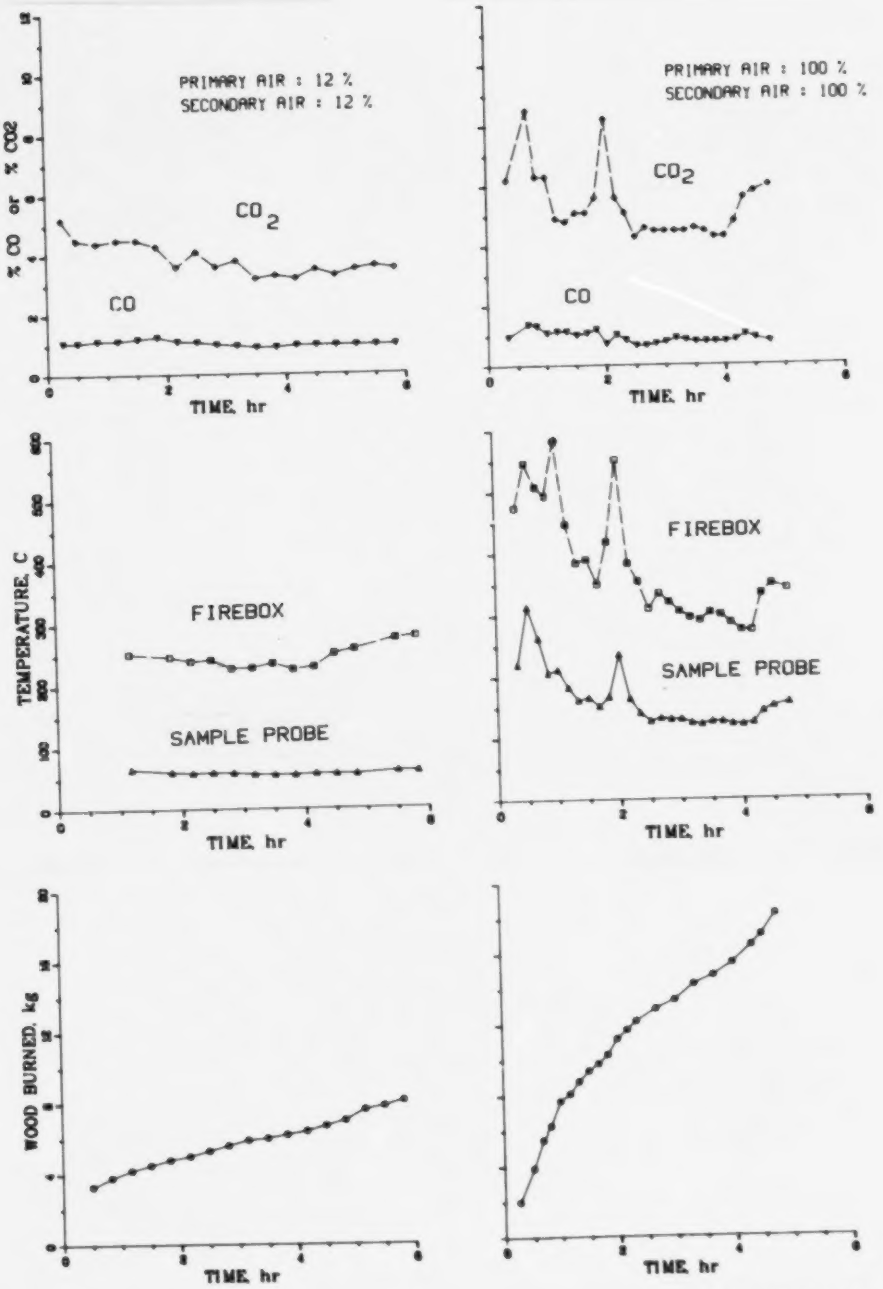
All experiments were performed in the following manner. The fire, initiated using kindling from the same wood supply used in the combustion experiments, was ignited before the stove door was closed and the combustion inlet-air level was set. At this time, the combustion process was allowed to reach equilibrium with respect to the observed temperature measurements before flue-gas sampling began. Sampling continued during the stable phase of the burn cycle (i.e., the flue-gas samples do not represent conditions during the start-up or end phases of the burn cycle).

Seasoned, locally obtained red oak was used to fire the stove. Experiments were performed with two log sizes, with approximate diameters of 0.12 m and 0.06 m. The former log size approximates that actually used by stove operators, while the latter is close to the size used in a prior study.[1]

RESULTS AND DISCUSSION

Emission sampling was carried out during individual combustion experiments employing the 0.12-m-diameter (large) logs at 12, 25, 50, and 100% of the maximum possible air opening for the stove; for the 0.06-m-diameter (small) logs, samples were obtained only at the 12, 50, and 100% air openings. In each experiment, particulates, condensibles, creosote, and gaseous samples were collected and CO and CO_2 concentrations were measured.

The nature of the data that were continuously monitored during the tests is illustrated in Fig. 2. These data obtained from tests using 0.12-m-diameter logs, include the following as functions of time: the



(a) 12% Air Opening

(b) 100% Air Opening

Fig. 2 Percentages of CO and CO_2, Sample-Probe and Firebox Temperatures, and Quantities of Wood Burned (top to bottom) versus Time for Two Different Air Openings (using logs 0.12 m in diameter in both cases).

weight of wood burned, the flue-gas sample-probe temperature, the firebox temperature and the percentages of CO and CO_2 present (from bottom to top, respectively, in the figure). The three sets of curves on the left present data from an experiment for which the air opening was 12%, and the corresponding curves on the right depict results for an air opening of 100%.

In the following discussion, we summarized the observed trends shown by these weight, temperature, and concentration data. We also note changes in these trends as the operator variables of air setting and log size are varied.

Burn rates can be computed from the slopes of the wood-burned-versus-time plots. Table 1 is a summary of linear least-squares determinations of slopes that were computed using experimental data taken after the first hour of the burn cycle (when the combustion process had stabilized).

TABLE 1. SUMMARY OF BURN RATES AS A FUNCTION OF AIR SETTINC AND LOG SIZE

Log Diameter (m)	Air Setting (opening, %)	Burn Rate (kg/hr)	Heat-Generation Rate (kcal/hr)
0.12 ↓	12	0.82	3,944
	25	1.27	6,119
	50	2.00	9,610
	100	2.58	12,404
0.06 ↓	12	3.89	18,714
	50	6.84	32,983
	100	7.73	37,285

From the table, it appears that log size has a marked effect: The burn rate for the 0.12-m-diameter logs varies from 0.82 to 2.58 kg/hr; in contrast, for the 0.06-m-diamter logs, the burn rate--over the same air-opening range--ranges between 3.89 and 7.73 kg/hr. Note that the burn-rate range for the larger log size employed in this study is similar to that reported in a study by Hayden et al.[6], while the burn-rate range for the smaller log size matches the results reported by De Angelis et al.[1] in a study that used similar small log sizes. These various studies, which utilized different commercial versions and generic types of stoves, indicate that commercially available stoves are designed with similar heat-output ranges. The effect of heat output is further illustrated in the last column of Table 1, where calculated heat-output values corresponding to the burn rates are listed. These values were computed on the assumptions that (1) the fuel was dry red oak, with a higher heating value of 4809 kcal/kg; (2) combustion efficiency was 100%; and (3) system thermal efficiency was also 100%. As was indicated earlier, wood-stove heat losses associated with realistic system thermal efficiencies and the typical moisture contents of wood likely would require a heat-generation rate of

10,000 kcal/hr, the lower end of the range reported in Table 1. Thus the tabulated results indicate that the particular stove used in this study has considerably more heat-generation capability than would be utilized a significant fraction of its operational time.

Similar trends also emerge for the other parameters shown in Fig. 2. For example, the sample-probe temperature for the experiments using 0.12-m-diameter logs varies from 55°C to approximately 174°C as the air opening is increased; for the 0.06-m-diameter-log experiments the corresponding range is approximately 200° to 400°C. A similar trend exists for the firebox temperature as a function of air opening, where firebox temperature is defined as the highest temperature recorded by the thermocouples. For the 0.12-m-diameter logs experimental temperatures ranged from approximately 250°C to approximately 360°C as the air opening was increased. In contrast, using the 0.06-m-diameter logs, the firebox temperature ranged from approximately 500°C to in excess of 800°C as the air opening was increased.

In addition to their environmental implications, the CO and CO_2 concentrations are of interest because they provide insight into the combustion process. The CO- and CO_2-abundance results did not exhibit as wide a variation with air-opening and log-size as did the other parameters discussed. For example, the CO concentration was generally around 1% or less over all the experimental conditions tested. In contrast, the CO_2 concentrations did exhibit a general increase with increasing air opening for both log sizes tested, the concentration being higher for the small logs than for the large logs. However, the observed CO_2 concentrations ranged between 3.7 and 10.9% (relatively low), suggesting that the combustion process did not utilize a significant fraction of the air that entered the stove. In other words, even at the lowest air settings, excess air was passing through the stove. The CO_2/CO ratio gives an indication of combustion efficiency, the measure of completeness of combustion. The observed trend for both log sizes was that combustion efficiency increases with combustion air opening, as illustrated by data shown in Fig. 2.

These experiments were not designed to determine stove thermal efficiencies, so some approximations were required to generate reasonable estimates for efficiencies in each of the experiments. The approach used was to perform a simple energy (sensible) and material (fuel) balance on the air, wood, and combustion products. Although the fuel losses take various forms (e.g., CO, gaseous hydrocarbons, condensibles, particulates, and creosote), only the CO fuel loss was considered here, because the necessary concentrations and heats of combustion were not available for the other heat-loss types.

These calculated efficiencies should be correct relative to one another, but they obviously overestimate stove efficiencies by the amounts of organic fuel losses not considered. However, in order to approximate these organic fuel losses, the calculated efficiencies were scaled by a constant factor to shift them into a typical range for air-tight stoves.[9] This constant factor was that need to shift the 0.12-m-diameter-log/12%-air-opening experiment's results, described in Table 1, to an arbitary value of 60% thermal efficiency. The key point here is that the relative values of these efficiencies are more important than the numerical values.

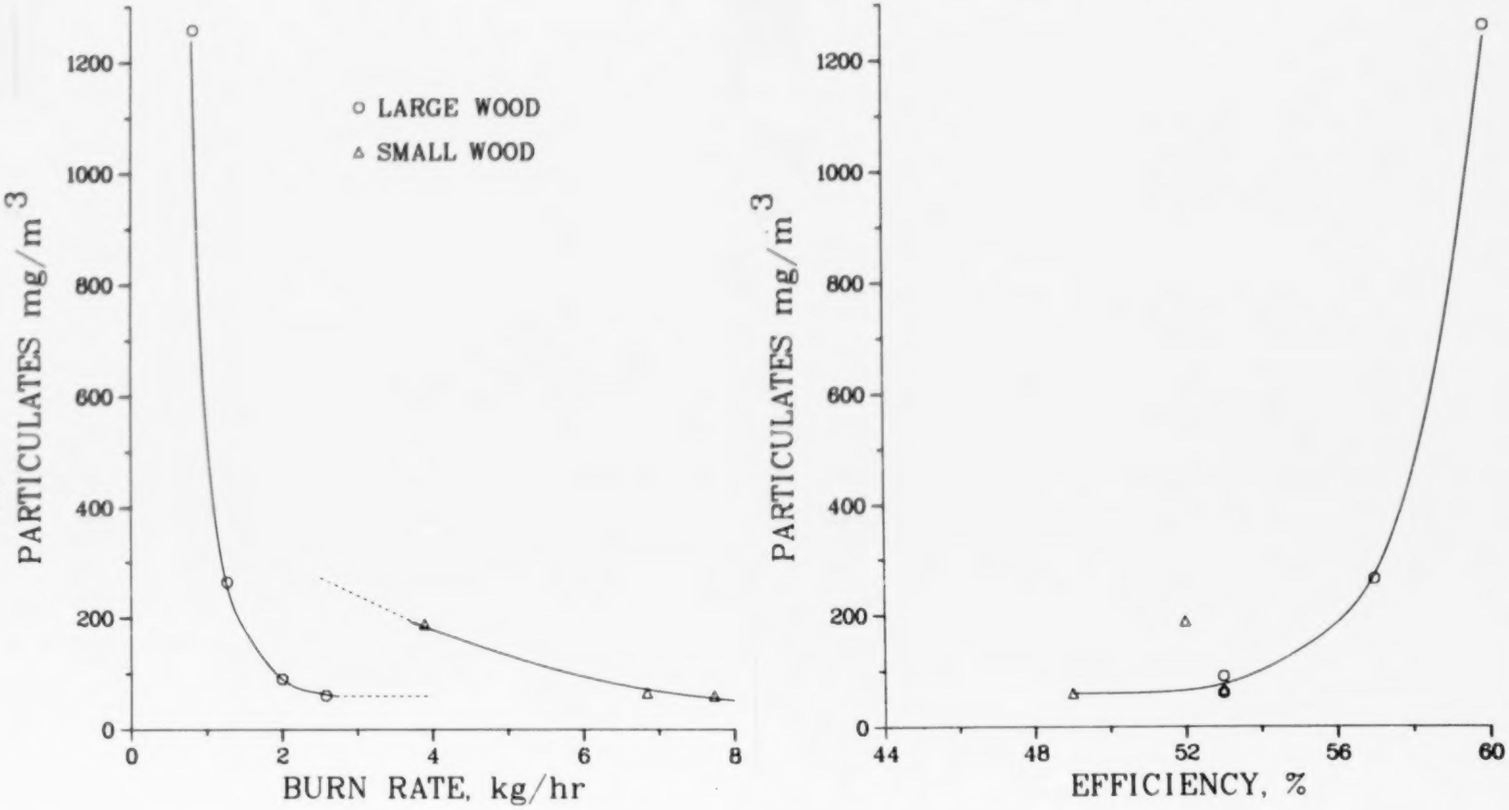
Calculated efficiencies were based on using a wood composed of 39.6% C, 35.4% O, 5.12% H, 0.08% N, 20.0% H_2O, and 0.16% ash, and on heats of combustion of 3690 and 67.64 kcal/kg (taken at a reference temperature of 20°C) for the wood and CO, respectively.

Mass-flow rates were estimated by performing a material balance on carbon from the assumed wood composition, the stack-gas CO and CO_2, and the observed burn rates of the wood. This estimation also required the assumption of negligible carbon losses to gaseous hydrocarbons, condensibles, particulates, and creosote--a necessary assumption, given the insufficient data on the production rates of these combustion components. We infer from the results of the 0.12-m-diameter-log/12%-air-opening experiment that these carbon losses probably were less than 5% of the carbon contained in the wood. Thus, the calculated total-mass-flow rates were those that accounted for all the carbon, either as CO or CO_2, at the observed CO and CO_2 concentrations of the stack gas.

Figure 3 (a) illustrates the particulate-matter emission results for the two log sizes tested. In this figure, the particulate concentration in mg/m^3 of stack gas is plotted against the burn rate in kg/hr. It is apparent that the relationship between particulate concentration and burn rate is dependent on the log size (i.e., it is not possible to draw one smooth curve through all the data from both log sizes). The effect of log size is more clearly illustrated if the particulate concentration is plotted against air opening, rather than against burn rate (cf. Table 1). The extrapolated (dashed) portions of the two curves in Fig. 3(a) emphasize that, at comparable burn rates, the small-log results appear to show higher particulate emissions than do the large logs. Moreover, the two curves have similar shapes--the particulate concentration increases as the burn rate decreases. However, the increase is markedly sharper for the large-log curve. These results demonstrate that log size significantly affects emissions, which, in turn, indicates a need to evaluate the environmental impact of log sizes that actually are used by stove operators. Our results also underscore the complexity of the chemical and physical interactions associated with particulate formation in wood stoves, suggesting a need for additional investigation.

Figure 3(b) shows the relationship between the particulate-matter concentration and the calculated thermal efficiency. In contrast to the relationship between particulate concentration and burn rate, the data here are adequately described by one curve, suggesting that there is no log-size effect. The shape of the curve indicates that as the thermal efficiency increases, the particulate-matter concentration rises rapidly. Comparison of Fig. 3 (a) with Fig. 3 (b) shows that the highest efficiency and highest particulate emissions are associated with the lowest burn rate. It is noted that the relationship between burn rate and thermal efficiency described here is in agreement with results reported by Hayden et al.[6]

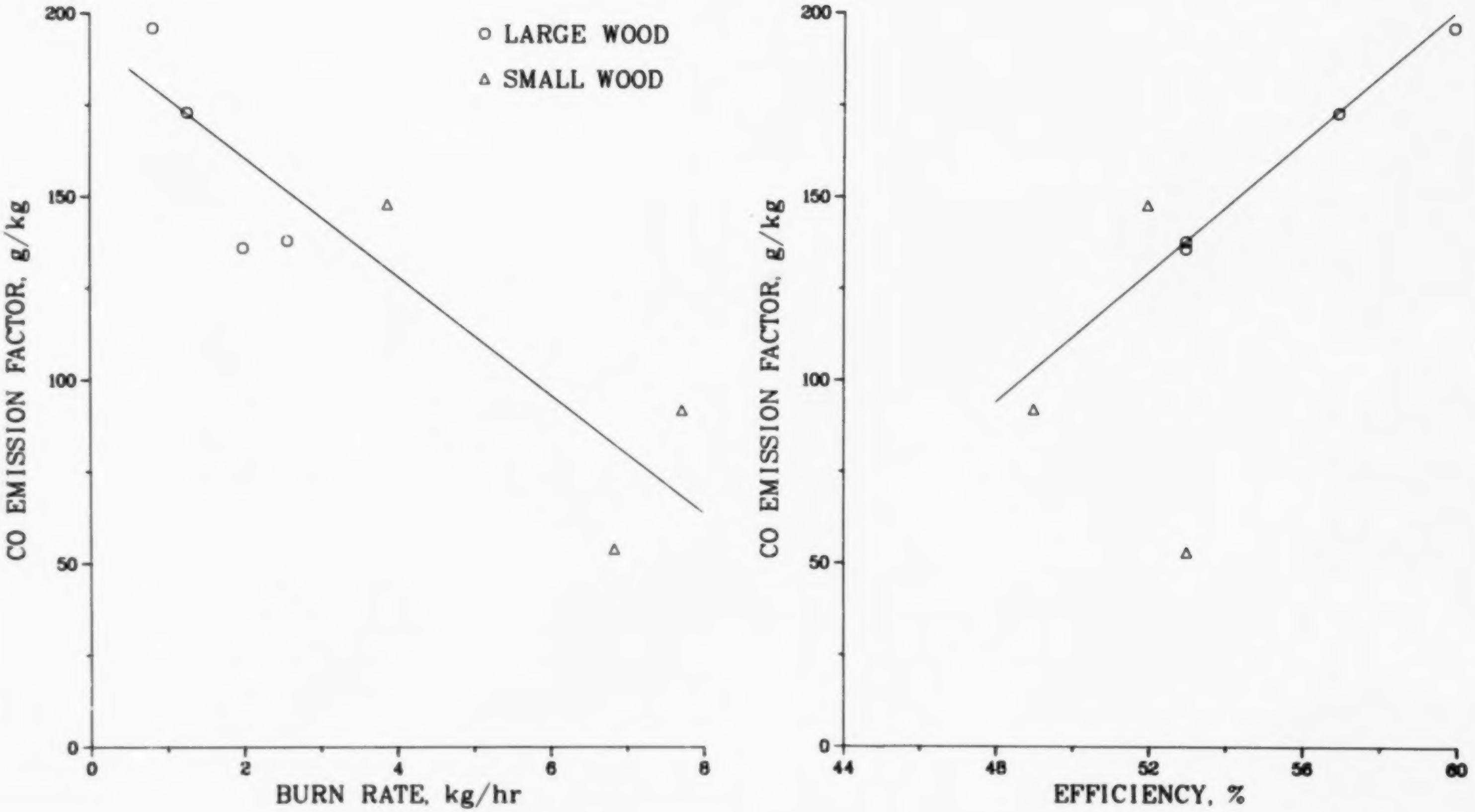
The CO emission results are summarized in Fig. 4; the CO emission factor, given in g/kg wood, is plotted against burn rate in Fig. 4 (a) and



(a) Particulate Concentration as a Function of Burn Rate (kg/hr)

(b) Particulate Concentration as a Function of Thermal Efficiency (%)

Fig. 3 Summary of Particulate Concentrations (mg/m^3) from Combustion of0.12-m-and 0.06-m-Diameter Oak Logs.



(a) CO Emission Factor as a Function of Burn Rate (kg/hr)

(b) CO Emission Factor as a Function of Thermal Efficiency (%)

Fig. 4 Summary of CO Emission Factors (g/kg) from Combustion of 0.12-m- and 0.06-m-Diameter Oak Logs.

against thermal efficiency in Fig. 4 (b). The CO emission factor was computed using the CO data earlier described in connection with Fig. 2. (Because the CO values were found to be fairly stable during the burn cycle of each experiment, an average CO concentration was computed. This average CO concentration then was used to compute the CO emission factor.) Figure 4 (a) shows that, in contrast to the particulate emission results, the relationship between the CO emission factors and the burn rate does not depend on the log size. All data points from both log sizes tested fit a linear least-squares curve with a 90% confidence level.

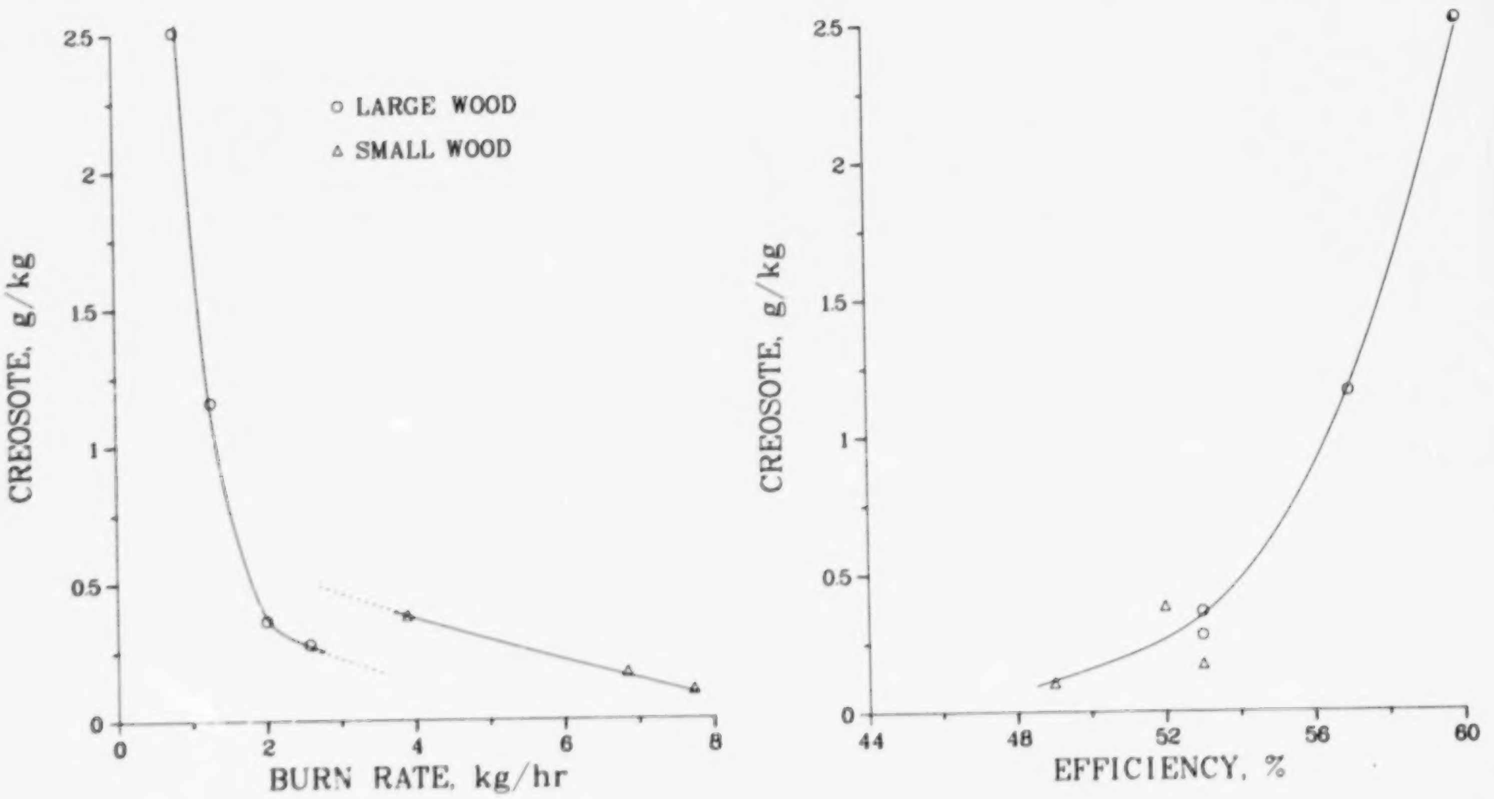
The results shown in Fig. 4 (b) are similar to the particulate emission results; that is, the relationship between CO emission and thermal efficiency is independent of log size. The linear least-squares curve was computed using all data points, with one exception--the data point from the small-log cases that is farthest off the line.

The general trends shown in these two plots--the decreasing CO emissions with increased burn rate and increasing emissions with rising thermal efficiency--are in agreement with results reported by Hayden et al.[6] We also note that the CO emission factors are of substantial magnitude, especially at the lowest burn rate (or, conversely, the highest thermal-efficiency conditions) at which stoves are being operated.

Creosote is not an environmentally harmful emission, because it condenses in the flue pipe and chimney. However, it is viewed as a fire safety hazard requiring continued maintenance for its removal from the system. Concern also has been expressed about potential health effects associated with creosote removal. Figure 5 displays the results obtained for creosote build-up in the flue pipe; again, creosote build-up, in g/kg wood burned, is plotted against burn rate and thermal efficiency, respectively. The similarity in the trends exhibited by the creosote build-up results and the particulate results described earlier (Fig. 3) are apparent:

- The creosote-build-up/burn-rate relation is strongly affected by log size.
- For both log sizes, the creosote build-up increases as the burn rate decreases, with the large-log build-up increasing markedly at the lower burn rates.
- At similar burn rates, the results suggest that the small logs exhibit greater creosote build-up than the large logs.
- No log-size effect appears with respect to thermal efficiency and creosote build-up.

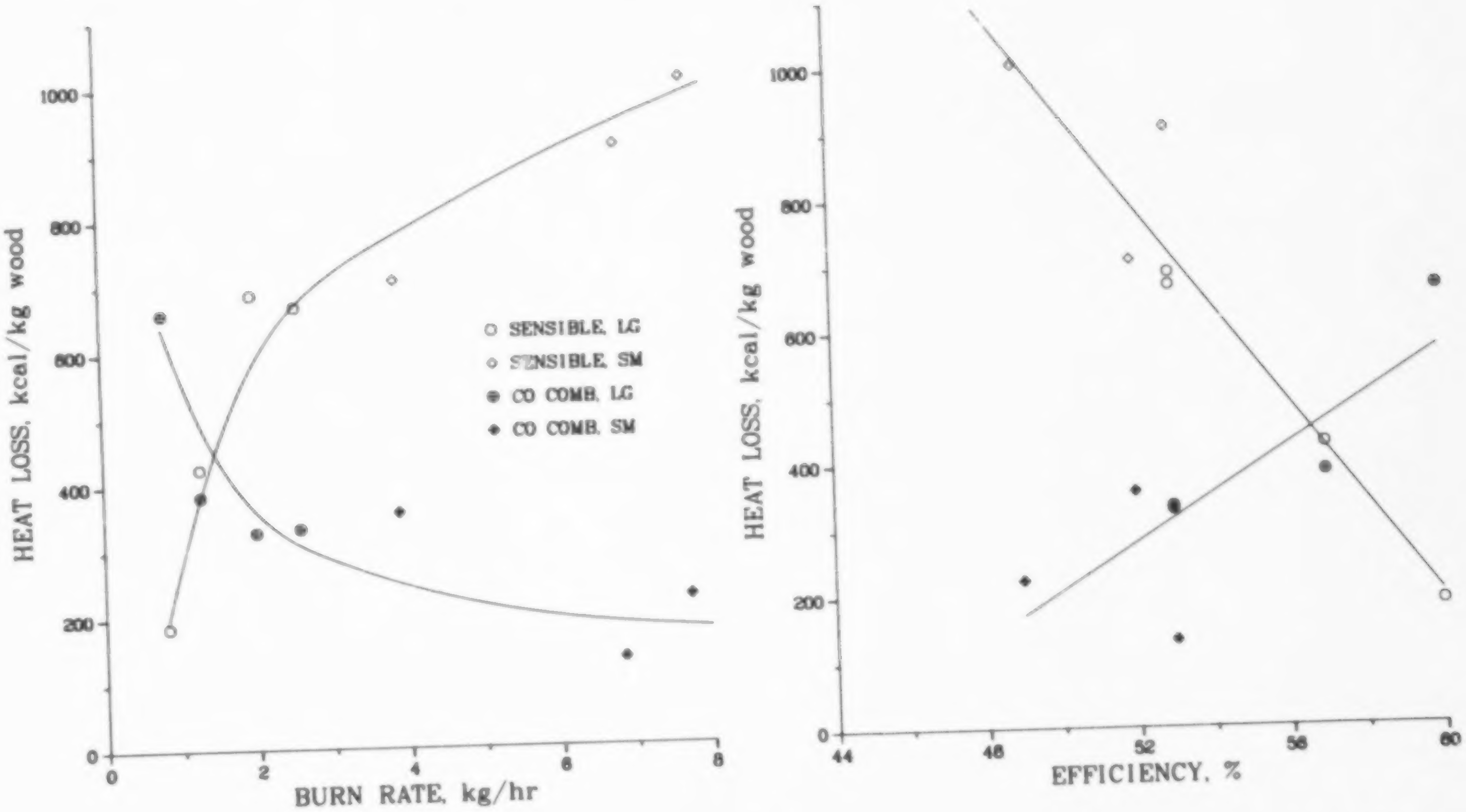
Figure 6 shows sensible- and CO-fuel-heat losses, computed from the data collected in this study, as functions of the burn rate and thermal efficiency. The sensible-heat losses were computed by performing an energy balance employing the sample-probe temperatures. The CO heat-of-combustion losses were calculated using the data described in Fig. 4. The trends



(a) Creosote Build-Up as a Function of Burn Rate (kg/hr)

(b) Creosote Build-Up as a Function of Thermal Efficiency (%)

Fig. 5 Summary of Creosote Build-Up (g/kg) from Combustion of 0.12-m-and 0.06-m- Diameter Oak Logs.



(a) Heat Losses as a Function of Burn Rate (kg/hr)

(b) Heat Losses as a Function of Thermal Efficiency (%)

Fig. 6 Summary of Sensible-and CO-Fuel-Heat Losses (kcal/kg) from Combustion of 0.12-m-and 0.06-m-Diameter Oak Logs.

exhibited, not the absolute heat-loss values, are of primary interest.

First, there is no apparent effect of log size. Trade-offs between the sensible- and CO-fuel-heat losses exist for both burn rate and thermal efficiency, but in opposing directions. The sensible-heat loss increases with increasing burn rate and decreases with increasing thermal efficiency. In contrast, the CO-fuel loss decreases with an increase in burn rate and increases as thermal efficiency increases. These results suggest that further improvements in stove efficiencies must focus on the recovery of fuel-heat losses; that is, air-tight-stove development probably has gone as far as possible in the recovery of thermal heat. Furthermore, improvements in the recovery of fuel-heat losses may also lessen the environmental impact associated with the use of air-tight wood stoves.

CONCLUSIONS

An experimental investigation that included the monitoring of selected emissions and parameters related to the operation of a commercially available, horizontally baffled, updraft, residential air-tight wood-burning stove has shown the following:

- The log size used in the stove has a pronounced effect on emissions, as well as on combustion parameters. Therefore, for realistic environmental assessments, testing must be done using log-size ranges actually employed by residential-stove users.

  The experiments showed, for example, that both particulate emissions and creosote build-up exhibited a log-size dependence with respect to the observed burn rate. At comparable burn rates, the combustion of the smaller logs appeared to produce greater concentrations of both particulates and creosote than did the burning of the large logs. In addition, for both log sizes tested, both particulate and creosote quantities increased as the burn rate decreased, with both parameters increasing markedly at the lower end of the burn-rate range when burning large logs. The CO emission results, in contrast, did not show a log-size dependence.

- From the viewpoint of environmental assessment, the results of this study also point out the importance of testing over an appropriate burn-rate range, one that is related to actual stove usage. Heat-output requirements for dwellings dictate usage on the lower end of the burn-rate range associated with commercial stove designs. The three parameters measured in this study--CO emissions, particulate emissions, and creosote build-up--all increase as the burn rate is decreased, with the latter two parameters increasing markedly at the lower end of the burn-rate range tested. The results show dramatically that the worst possible effects associated with these parameters do actually occur under the conditions at which such stoves are operated a significant fraction of time.

- Our results indicate that the relationship between system thermal efficiency and the CO and particulate emissions, as well as the creosote build-up, is the opposite of what would be desired. The highest system efficiencies are observed when the highest pollutant concentrations occur (i.e., under low-burn-rate conditions). Also, the observed relationships of these various concentrations to system efficiency do not exhibit a dependence on log size. This finding has positive implications in reference to recommended standarized thermal-efficiency testing methods,[10] where small-size wood is specified in the test methods.

- The heat-loss calculations indicate a trade-off between sensible- and fuel-heat losses as the efficiency of the stove is increased--as the sensible-heat loss decreases, the CO-fuel-heat loss increases.
- In addition to the log-size and burn-rate effects described above, the trends with respect to the firebox temperature may have environmental significance. The wide range of temperatures may well play a role in the nature of the chemical species emitted. Chemical characterization studies now underway will ascertain if this speculation is valid.

REFERENCES

1. D. G. DeAngelis, D. S. Ruffin, and R. B. Reznik, "Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment," EPA-600/7-80-040.

2. S. S. Butcher and E. M. Sorenson, "A Study of Wood Stove Particulate Emissions, J. Air Pollut. Cont. Assoc., 29, 724 (1979).

3. J. A. Cooper, "Environmental Impact of Residential Wood Combustion Emissions and Its Implications," Proceedings Document for Wood Heating, Seminar VI, pp. 26-55, Wood Energy Institute, Washington, D.C. (1980).

4. J. E. Duncan, K. M. Morkin, and M. P. Schmierback, "Air Quality Impact Potential From Residential Wood-Burning Stoves," presented at 73rd APCA Annual Meeting, Montreal, Quebec (June 22-27, 1980).

5. J. M. Allen, "Control of Emissions From Residential Wood Combustion by Combustion Modification," Proceedings of the Joint Symposium on Stationary Combustion NO_x Control, Volume III: NO_x Control and Environmental Assessment of Industrial Process Equipment, Engines, and Small Stationary Sources, IERL-RTP-1085 (October 1980).

6. A.C.S. Hayden and R. W. Braaten, "Performance of Domestic Wood-Fired Appliances," presented at 73rd APCA Annual Meeting, Montreal, Quebec (June 22-27, 1980).

7. A.C.S. Hayden, R. W. Braaten, and T.D. Brown, "Oil Conservation in Home Heating," ASME Journal of Power, 99, Series A, 413 (1977).

8. A.C.S. Hayden, R. W. Braaten, and T. D. Brown, "Emissions and Energy Conservation in Residential Oil Heating," J. Air Pollut. Cont. Assoc., 28, 669 (1978).

9. R. E. Hall and D. G. DeAngelis, "EPA's Research Program for Controlling Residential Wood Combustion Emissions," J. Air Pollut. Cont. Assoc., 30,862 (1980)

10. T. T. Maxwell, D. F. Dyer, and G. Maples, "Efficiency and Heat Output Measurements for Residential Wood Heating Appliances," Proceedings Document for Wood Heating, Seminar VI, pp. 119-228, Wood Energy Institute, Washington, D.C. (1980).

Session 3: EMISSIONS CONTROL TECHNIQUES FOR WOOD BURNING APPLIANCES

Chairman: Wade H. Ponder
U.S. Environmental Protection Agency
Research Triangle Park, NC

CATALYTIC COMBUSTION IN RESIDENTIAL WOOD STOVES

by: Robert V. VanDewoestine,
Manager, Special Process Research Dept.
Frank Zimar,
Senior Research Chemist
and
Roger A. Allaire,
Senior Project Engineer
Research and Development Division
Corning Glass Works
Corning, N.Y. 14830

ABSTRACT

A catalytic combustor for wood stoves has been developed that reduces accumulation of creosote in flues and chimneys, reduces air pollution and improves stove efficiencies. The potential now exists to bring wood combustion to levels of safety and efficiency comparable to fossil fuel combustion.

INTRODUCTION

For several decades wood was not much used as a fuel for residential heating in the United States. Fuel oil, natural gas and electricity were so available, cheap, efficient, clean and safe that wood was virtually abandoned. However, high prices and potential (or real) shortages of conventional fuels have caused millions of persons to install and use woodburning stoves and furnaces. With this increase in wood usage, there has been a resurgence of the safety and pollution problems involved with wood heating. For wood heating to continue its growth as a percentage of United States energy consumption, the technology needs to be improved.

The fundamental problem of residential wood combustion is that no economical method exists for metering wood into the firebox to produce the required heat output. Large amounts of fuel are loaded infrequently and the combustion rate is controlled by the amount of available oxygen. As the wood sits in the hot firebox, it is heated to the point where combustible volatile components are driven off. These volatiles are often not burned in the stove because of a poorly distributed and limited oxygen supply. By the time secondary air is introduced and mixed with the combustible gases, temperatures are usually too low to bring about any significant degree of burning. As a result of the incomplete volatile combustion, unburned hydrocarbons and carbon monoxide are released from the stove to the chimney. These products either condense in the chimney or are released into the atmosphere. The condensed materials present the danger of chimney fires and the released materials can cause significant air pollution.

Figure 1 shows a typical wood stove. It is basically a box with a variable orifice to control combustion air and a fixed-size exit to the chimney. There are hundreds of variations on this design involving grates, insulation, thermostatically controlled combustion air, baffles, windows and multiple combustion chambers. While some of the variations are more effective than others, all still suffer from the same problem as the basic stove. If the firebox is hot enough to cause complete combustion of the wood and evolved combustible gases, the burning cycle proceeds very rapidly, giving too much heat for a short time. If the combustion rate is restricted to give a reasonably steady heat output, the combustible gases are not completely burned in the stove.

A method is needed which causes evolved gases to be burned at the temperature existing in a stove operating under controlled conditions. These temperatures are typically in the range of 200 - 400°C. Noble-metal catalysts on ceramic honeycomb substrates have been used to perform this function in automotive exhaust systems (see Figure 2). The catalyst reduces the ignition temperatures of the hydrocarbons and carbon monoxide so that they start "burning" around 230°C. The heat release from this burning raises the temperature of the catalyst and its support which in turn increases its catalytic activity. The high temperature cracks oily smoke droplets and leads to their oxidation. The temperature rise continues until the system reaches a temperature at which there is equilibrium between the inlet gas temperature, flow rate and the amount of oxidizable material. This temperature is typically 600 - 900°C for a properly sized catalyst system. At these temperatures, oxidation proceeds very rapidly to completion if the catalytic device has sufficient volume and internal surface area.

LABORATORY TESTING

Experiments were started to define catalytic combustor geometries suitable for use with woodburning stoves. A standard stove was equipped with a catalytic combustor in the exhaust stack at the stove exit as shown in Figure 3. This location should not be used commercially, but was convenient for laboratory experiments. Stove modifications also included instrumentation to determine combustor performance and

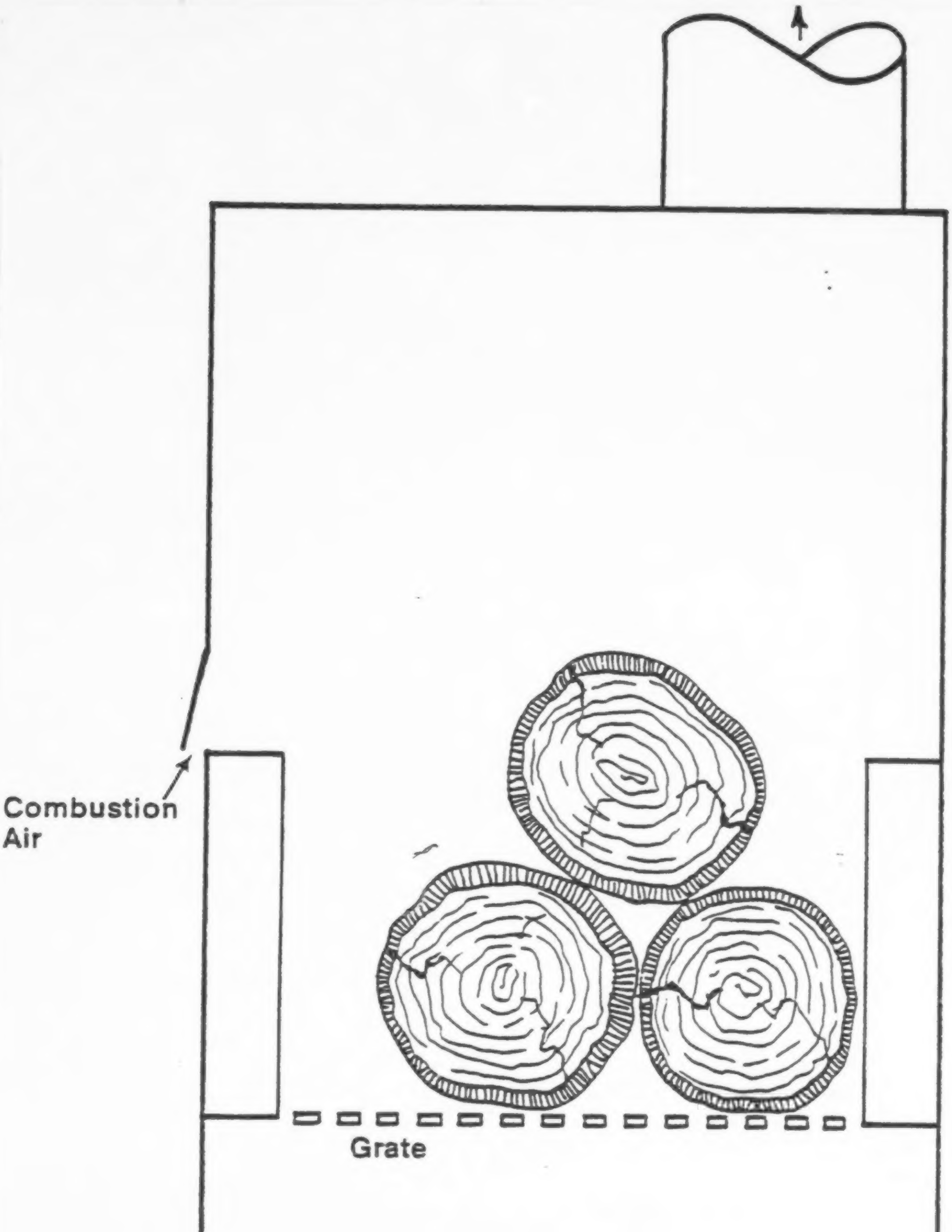

Combustion Air
Grate

Figure 1. Conventional Wood Stove.

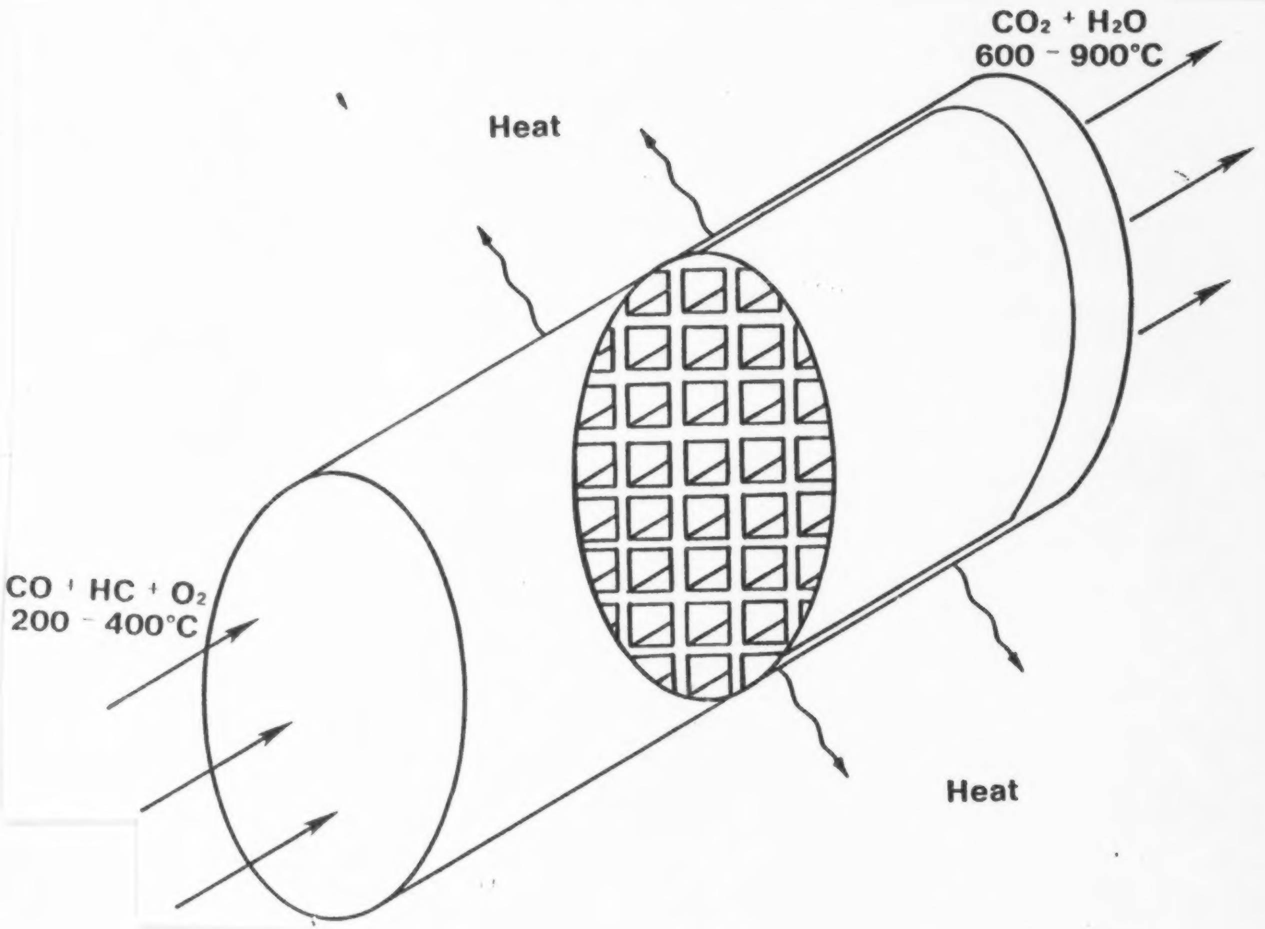

$CO_2 + H_2O$
600 - 900°C
Heat
Heat
$CO + HC + O_2$
200 - 400°C

Figure 2. Catalytic Combustion System Schematic.

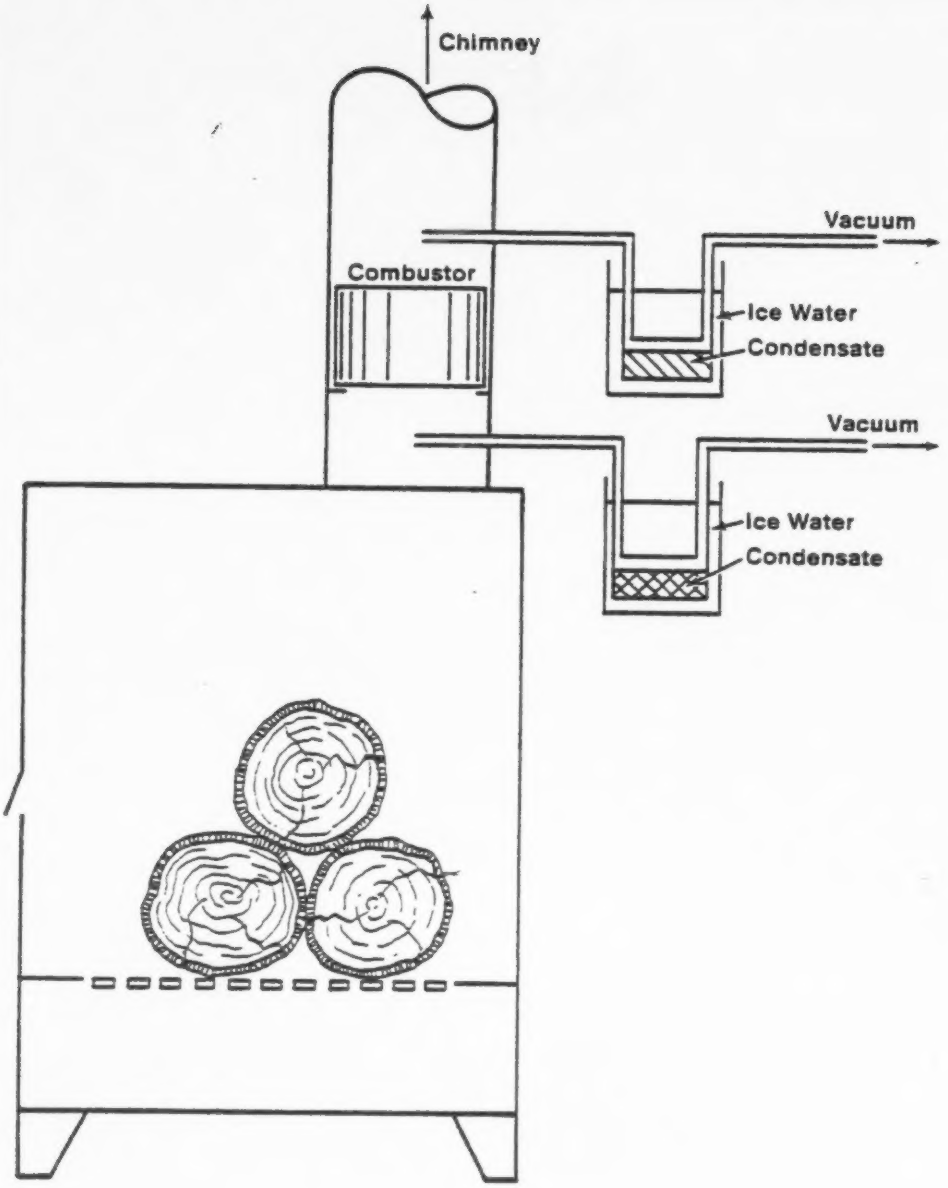

Chimney
Vacuum
Combustor
Ice Water
Condensate
Vacuum
Ice Water
Condensate

Figure 3. Catalytic Combustor Experimental Installation (Not suitable for residential use).

temperatures. Combustor effectiveness was measured by the simultaneous withdrawal of stack-gas samples from above and below the combustor. The samples were condensed in ice water-cooled tubes. After a very careful drying procedure, the contents of the tubes were weighed. The ratio of the weights of the condensed material from above and below the combustor was used as a measure of combustor performance.

The volume and internal geometry of the combustor determine its catalytic and pressure drop performance. Figure 4 shows a schematic drawing of a combustor. It is defined by its diameter, length, inside cell dimension and the wall thickness between cells. The wall thickness and cell dimension can be combined to give the cell density in cells per square inch of frontal area, N.

$$N = \frac{1}{(X + T)}^{2}$$, where X = inside cell dimension
and T = wall thickness

Both catalytic activity and pressure drop are strong functions of the cell density. Preliminary calculations based on estimated flow rates had shown that a nine-cell/in^2 combustor 5 5/8" in diameter would have a pressure drop low enough that it would not significantly affect stove operation. Experiments were also run with 16 and 25-cell/in^2 combustors of the same diameter. None of these combustors interfered with stove draft during normal operation with the doors closed. With the doors open, the extra flow cannot be handled by the combustor and has to be accommodated by a bypass. Combustors with cell densities higher than 25 cells/in^2 were found to be unsuitable unless they were much larger than six inches in diameter. Since these sizes are not commercially available, little work was done with them. There was also concern that high cell densities would lead to plugging problems.

Data on the amount of condensable material below and above the combustor were taken 10 minutes after loading eight pounds of wood into a hot firebox. The data were reasonably consistent, considering the variability of the wood combustion process. The amount of condensables at the combustor inlet could vary by a factor of four for stove conditions that were established to be constant. Table 1 shows the condensable material reduction for 9, 16 and 25-cell/in^2 combustors of various lengths. There were significant reductions in condensables for all geometries tested. Better combustor performance is related to increased internal surface area but is also a function of cell size. Internal area is increased by increasing combustor volume or by increasing the number of cells per square inch of frontal area.

Figure 5 shows another interesting result. The total

TYPING GUIDE SHEET

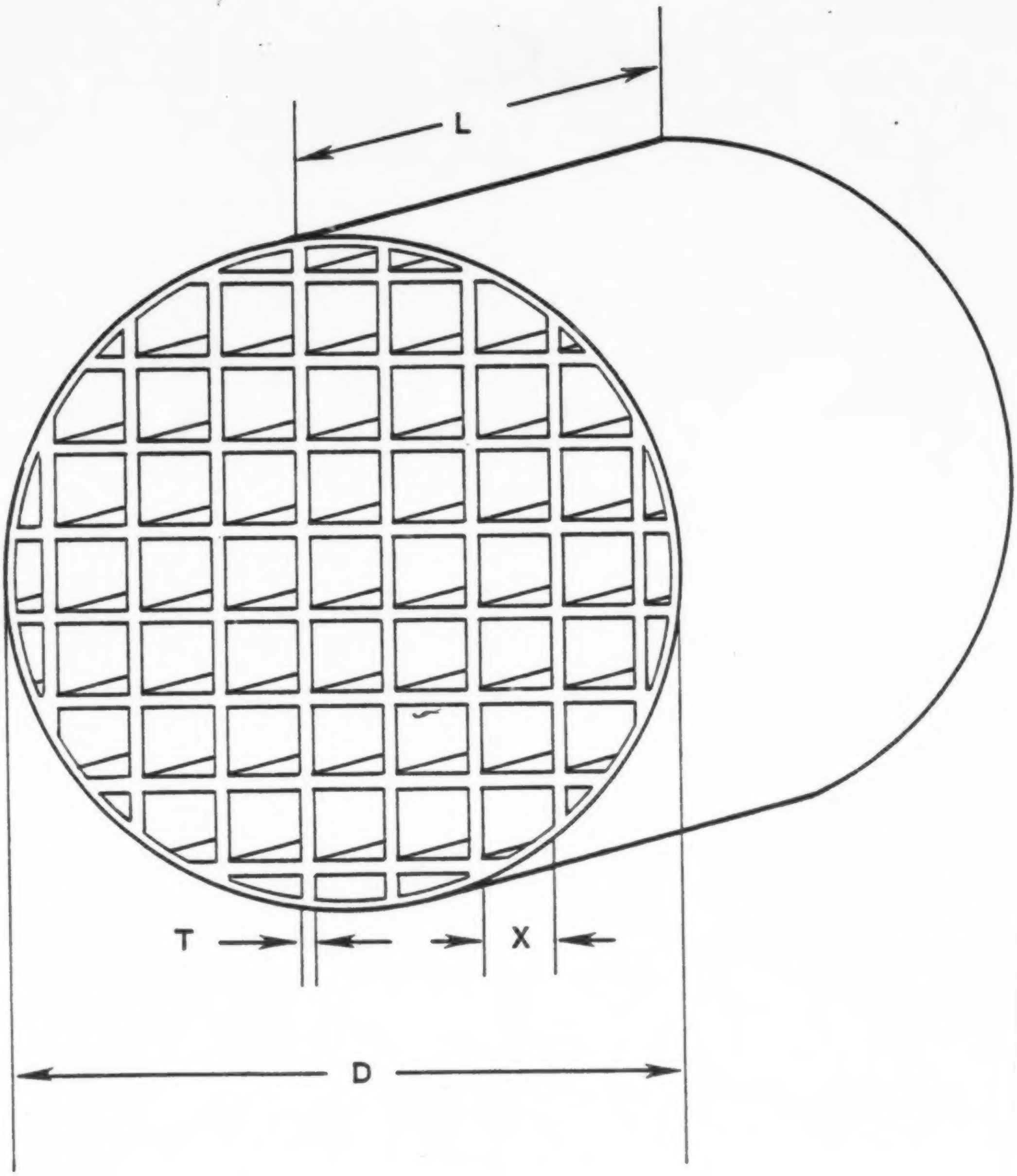


Figure 4. Catalytic Combustor Geometry.

TABLE 1. CATALYTIC COMBUSTOR PERFORMANCE

CELLS IN^2	LENGTH (IN)	DIAMETER	INTERNAL SURFACE AREA-IN^2	AVERAGE % CONDENSIBLE REDUCTION
9	6	5 5/8	1510	84
16	3	5 5/8	1015	85
16	6	5 5/8	2030	95
25	3	5 5/8	1245	89
25	2	5 5/8	830	75

$$\text{Internal Area} = (\text{Combustor Volume}) \quad \frac{4X}{(X + T)^2}$$

TYPING GUIDE SHEET

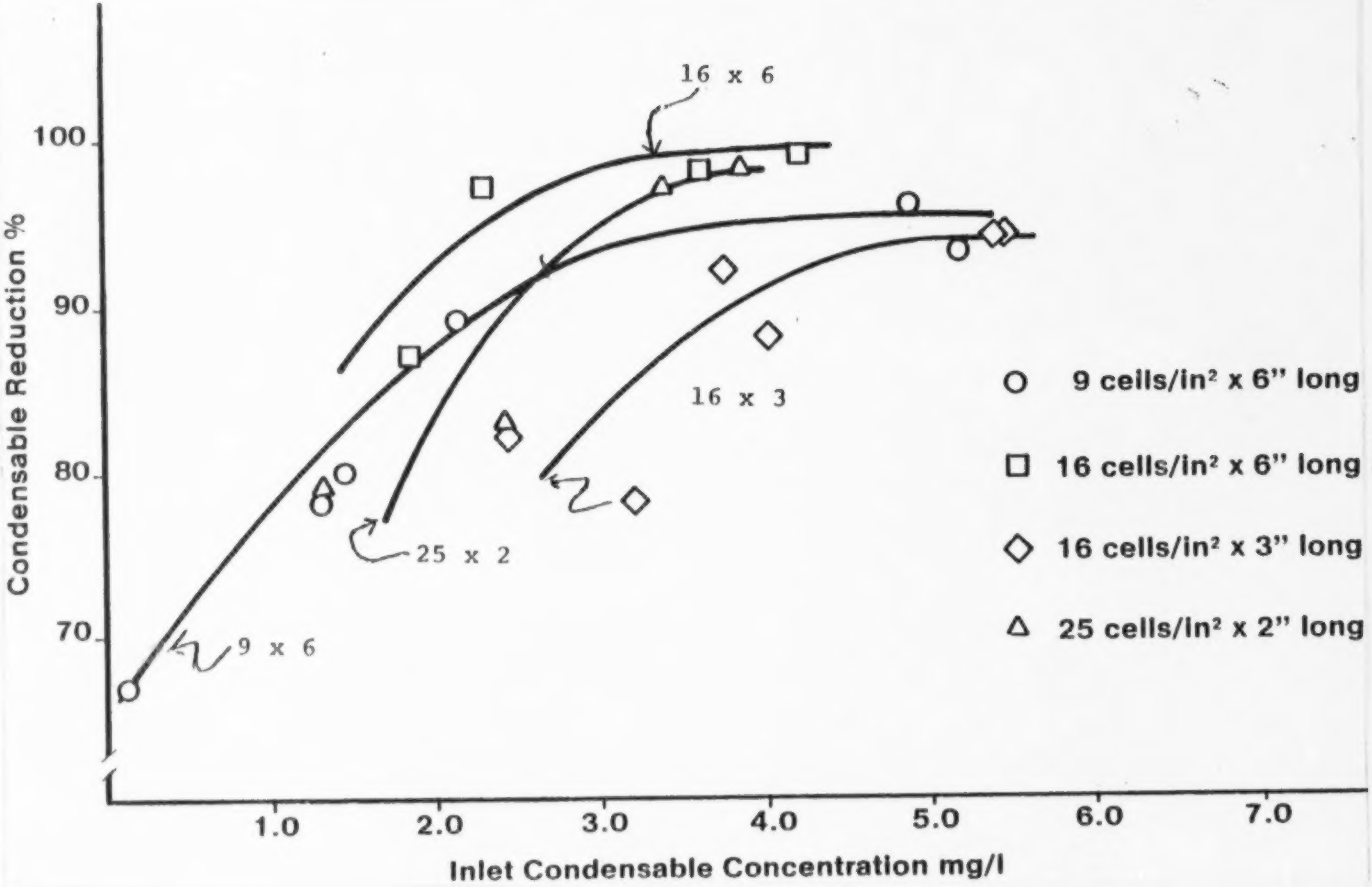


Figure 5. Combustor Efficiency As A Function Of Inlet Pollutant Loading.

emissions were lower when there was a lot of combustible material coming from the stove than when there was just a little. The combustor is more efficient at the higher inlet loadings. With additional combustible material in the inlet gas stream, the combustor runs hotter, increasing its ability to complete the burning process.

No attempt was made to identify the change in chemical species that occurred in the combustor. Observation of the collecting tubes showed a tendency for the materials trapped downstream of the combustor to be soot-like particles rather than the tars which existed upstream, but this change was not quantified.

Field Testing

Field testing was done with 16-cell/in^2, three-inch long by 5 5/8-inch diameter combustors. This geometry represents a good compromise between catalytic activity, pressure drop and cost. Figure 6 shows the firebox and combustor temperatures through a typical wood loading cycle lasting about 10 hours. The temperature of the combustor is a measure of its activity, while the temperature rise across the combustor is a measure of the heat which would have been lost by combustible materials being released to the chimney. The firebox was loaded at hour 21 in Figure 6. The combustor temperature increased rapidly (light off) for firebox temperatures around 300°C. These conditions were sustained for several hours as the volatiles were distilled out of the wood. The combustor temperature gradually decreased as the volatiles were exhausted. Toward the end of the burn, the combustor temperature increase was largely maintained by oxidation of CO from the charcoal in the firebox. At hour 30, the firebox was reloaded and the cycle repeated.

After three months of continuous use there was no measurable buildup of condensables in the flue pipe leading to the chimney, only a thin (.015 inch) layer of dark soot. Prior to the installation of the combustor it only took one to two months for the six-inch flue pipe to plug down to three inches at the point where it went through the chimney thimble.

Rigorous efficiency-increase measurements have not yet been made, but wood consumption appeared to decrease about 20 percent with combustor use. Exhaust pipe temperatures are increased somewhat by the combustor, but can be held well within UL specifications by proper design. The temperatures are far below those that would be experienced in a chimney fire.

The primary purpose of the present work was to end the problem of combustible material condensing in the chimney. This was accomplished by the 16-cell/in^2, three-inch long combustor for typical air-tight radiant heating wood stoves.

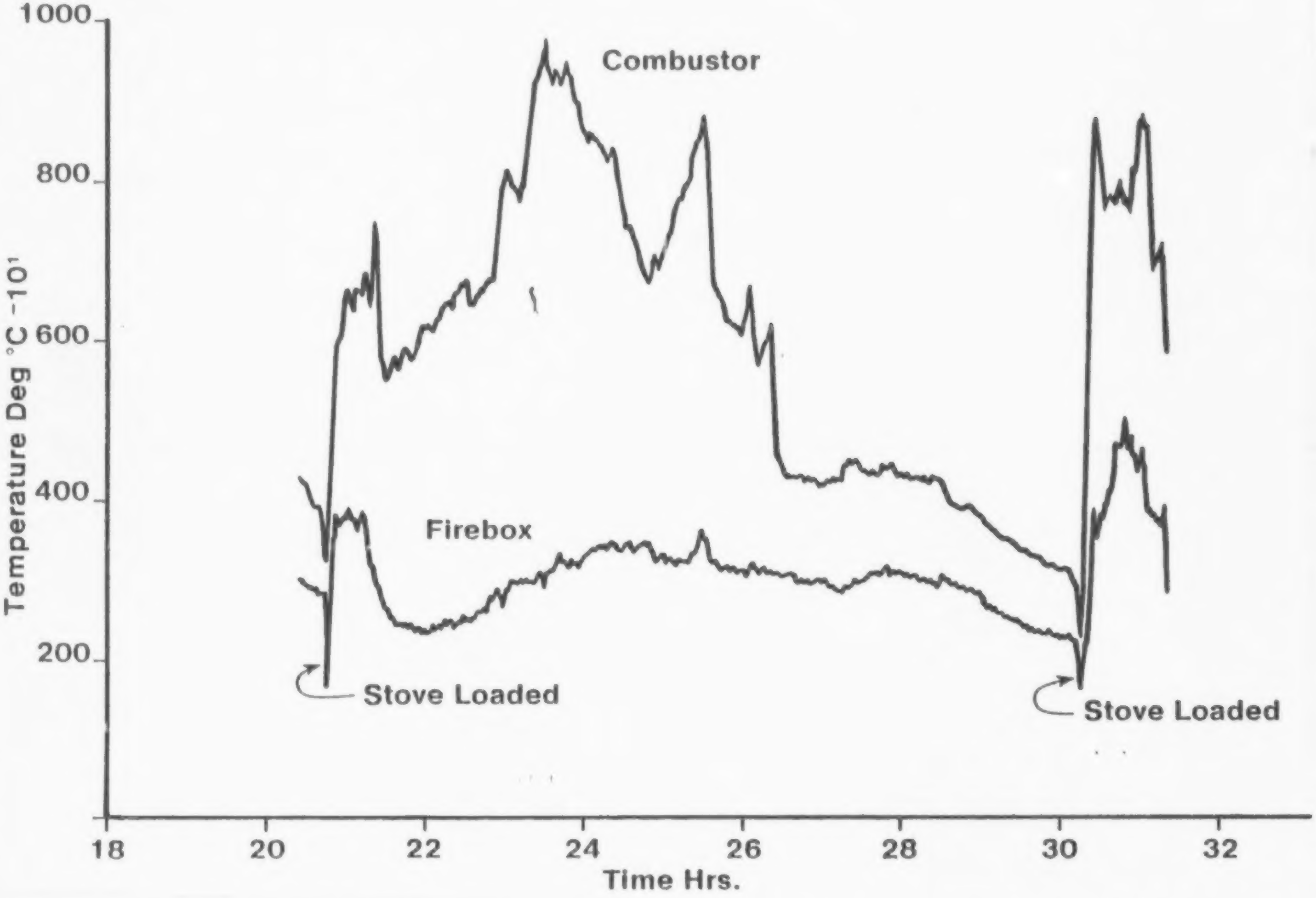


Figure 6. Firebox And Combustor Temperatures For A Complete Loading Cycle.

A combustor of this volume also increased efficiency and caused a reduction in emitted unburned hydrocarbons. Further reduction of emitted hydrocarbons and increase in stove efficiency can be achieved by increasing the combustor volume.

New Stove Designs --

Relatively minor design changes are necessary for new stoves to accommodate combustors. Figure 7 shows a design which includes the necessary features. The combustor is mounted in the stove so that it receives the hottest possible gases directly from the combustion chamber. To account for the added pressure loss in the combustor, a bypass is necessary when the firebox door is open for loading and for starting a fire. Finally, there is often need for secondary combustion air to insure that oxidizing conditions exist at the combustor inlet. As with other stove designs there are many possible variations on the basic design. One such modification would be to incorporate a heat exchange surface in the upper chamber to remove the additional heat generated in the combustor.

In the field tests conducted to date, the catalytic combustor has been effective in significantly reducing chimney creosote accumulations and improving stove efficiencies. Several major stove manufacturers are now working to incorporate catalytic combustors into their stove designs. This has been a major step forward in improving the safety and effectiveness of wood combustion. The potential now exists to bring wood combustion to levels of safety and efficiency comparable to fossil fuels without radical changes to stove designs or methods of operation.

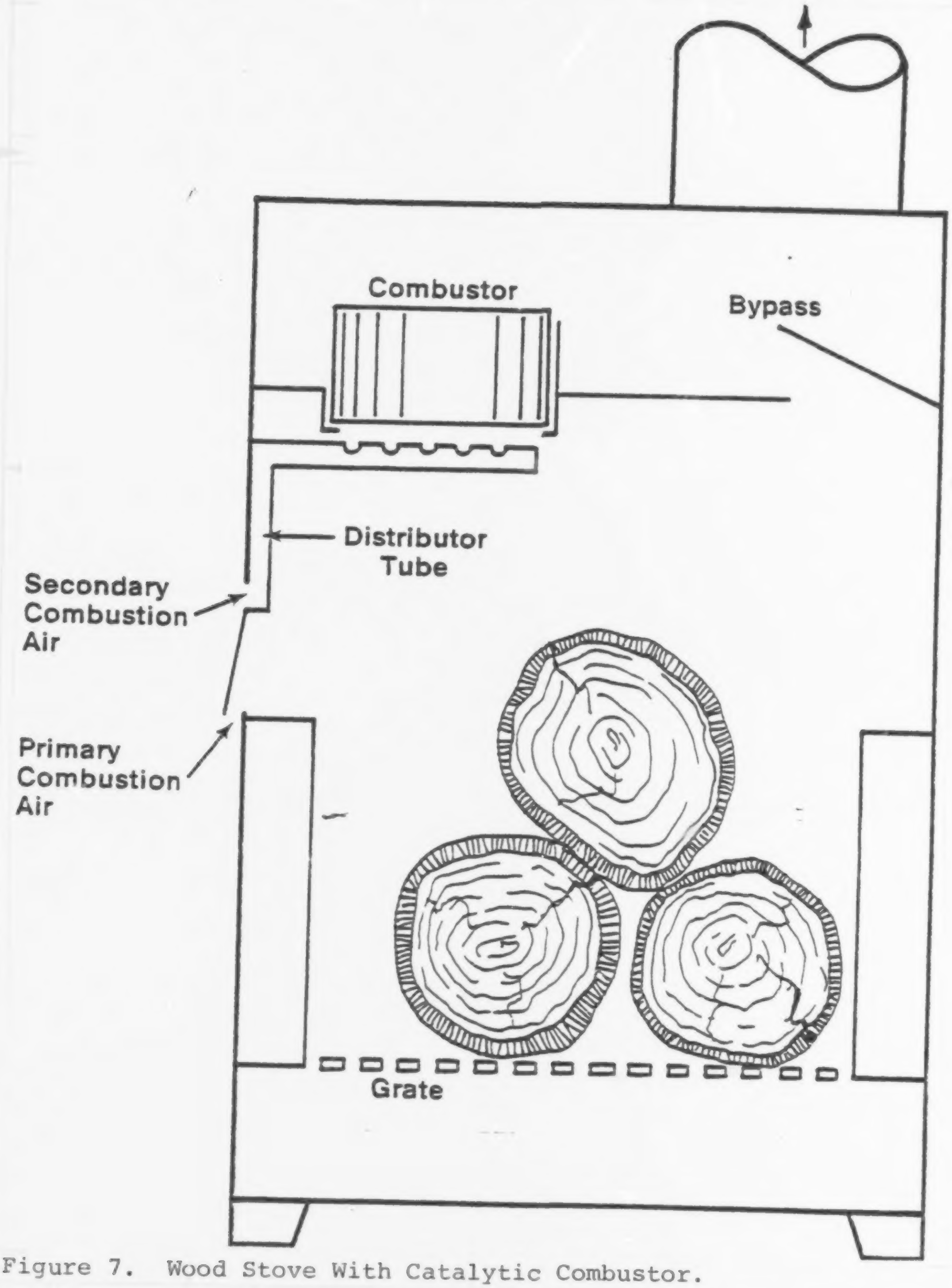

Combustor
Bypass
Distributor Tube
Secondary Combustion Air
Primary Combustion Air
Grate

Figure 7. Wood Stove With Catalytic Combustor.

CATALYTICALLY ASSISTED COMBUSTION IN
RESIDENTIAL WOOD-FUELED HEATING APPLIANCES

Invited paper to EPA-conducted conference
on Wood Combustion Environmental Assessment
held in cooperation with
The Wood Heating Alliance 1981 International
Trade Show and Wood Heating Seminar

New Orleans, Louisiana
February 21-24, 1981

by

J. W. Shelton

Shelton Energy Research
P.O. Box 5235
Santa Fe, NM 87502

Catalytically Assisted Combustion in Residential Wood-Fueled Heating Appliances

ABSTRACT

Both safety and performance of ceramic honeycomb type catalytic combusters were investigated. The potential safety issues of high temperatures, flow resistance and creosote plugging all appear to be solvable with proper engineering of the combuster and the appliance.

A Riteway Model 37 wood stove was modified to accept a catalytic combuster. The stove's energy efficiency was measured both with and without the catalyst. The catalyst increased the unit's overall energy efficiency by from 3 to 9 percentage points--or from 6 to 18 percent.

INTRODUCTION

Catalytic combustion of wood smoke in residential wood heating systems offers potential advantages of substantial reductions in creosote[1] accumulation and in air-polluting emissions, and substantial increases in overall energy efficiency.

Previous work[2, 3] indicates that between 5 and 30 percent of the chemical energy content of the wood fuel leaves a typical wood heater unburned as smoke. Smoke is an air pollutant, and when condensed inside the chimney or connector becomes creosote. Creosote is of concern because (1) it can burn inside the connector and chimney, and such chimney fires are potentially dangerous both to the house and to the chimney; (2) creosote can be corrosive to chimney systems; (3) most creosote deposits act as thermal insulation, decreasing the heat output of the system (particularly systems with exposed interior chimneys); and (4) in extreme cases, where liquid creosote is not contained inside the venting system, it stains and constitutes an odor problem.

Increasing the combustion efficiency of a wood burning appliance by catalytic or any other means has three potential benefits, but not all are necessarily achieved simultaneously. Total emissions of combustibles are of course reduced. Creosote is reduced for one or both of two reasons: smoke density is reduced, and if some of the extra heat released by virtue of the better combustion is allowed to flow up the chimney, flue gas temperatures are also higher. Overall energy efficiency is increased to the extent that the extra heat released is extracted and used for space heating. It is plausible that many catalytically assisted systems will simultaneously achieve both more heat output and higher stack temperatures, but if desired, all the extra heat could be used for space heating. Creosote would still be reduced due to the lower concentrations of the creosote precursors in the flue gas.

This paper summarizes two projects on catalytic combustion funded by Corning Glass Works. The first concerns safety aspects and the second, thermal performance.

Project No. 1

SAFETY

The major concern of this research project was the safety of catalytic combustion devices in the form of coated ceramic honeycomb monoliths. The major areas of concern were (1) plugging of the monolith; (2) high temperatures resulting from catalytic combustion; and (3) smoke spillage from the appliance due to flow resistance in an unplugged monolith. The intent was to investigate worst-case situations.

Plugging

If a monolith were installed without any bypass provision, and should the monolith become plugged with creosote, the whole heating system would become disabled for lack of venting and substantial amounts of smoke could spill out of the system. The life-safety hazard of smoke spillage depends on the amount of smoke released, and on whether the occupants are awake or asleep when the spillage starts (assuming there is no operating smoke alarm).

Both the amount of spillage and the likelihood of the occupants being asleep at the onset of spillage depend on the rate of plugging. If the monolith became plugged within a few hours, the plugging could occur with a large hot fuel load still in the appliance and thus a substantial amount of smoke could be released into the building. In addition, if plugging occurs within hours, occupants could be asleep before spillage starts.

On the other hand, if the plugging process takes days or longer, (1) the operator is more likely to become aware of the problem before it becomes a health hazard, and (2) should complete blockage occur the spillage rate would be smaller since the appliance would be cooler due to the combustion air flow having been low for a considerable time before. If plugging occurs so slowly that the process is comparable to the gradual restriction in a chimney or connector due to creosote buildup, then the fact that the monolith could become plugged would constitute no additional hazard.

Because it was the intent of this project to seek worst-case situations, uncatalyzed monoliths were used for most plugging tests. Catalyst activity can degrade in the field due to (1) the use of fuels and additives which poison the catalyst (possible examples are painted wood, chemical chimney cleaners, fire colorants and household trash); (2) masking of the catalyst with ash, soot and tar; and (3) high temperature degradation of the wash coat. Uncatalyzed monoliths should closely simulate an inactive catalyzed monolith. In addition the plugging of uncatalyzed and catalyzed substrates should be similar if smoke temperatures are always well below the "light-off" temperature of the catalyst.

Plugging tests involved a wide variety of conditions including 4 species of wood, moisture contents varying from about 35 percent (on a moist-wood basis) down to zero percent, average flue-gas temperatures at the monolith from 75 up to about 300° C. (as measured with unshielded thermocouples), average flue-gas velocities from about 0.3 to 1.3 meters per second, and smoke densities varying over the full range normally encountered in wood stove operation. A single type of stove, the Riteway Model 37, was used for all plugging tests since this stove was capable of producing the full range of desired smoke densities, velocities and temperatures. The monoliths were located in a vertical section of stovepipe 2 to 3 feet downstream from the collar on the stove (Figure 1).

The degree of plugging was assessed in three ways: (1) the pressure drop across the monolith; (2) visual inspection of the monolith, documented with photographs; and (3) the effects on stove operation--smoke spillage out of small cracks and inability to obtain high combustion rates despite wide open air inlet damper.

The experimental results indicate that plugging is a potential problem. Under the intentionally worst-case conditions of a smoldering fire and an uncatalyzed substrate 2 to 3 feet from the stove in the stovepipe, essentially total plugging can occur in a few hours. "Total" plugging was evidenced (1) by there being essentially no visible open path through the honeycomb structure; (2) by essentially continuous smoke spillage out of stovepipe joints and other cracks or holes below the substrate; (3) by very low combustion rates even with the stove's air inlet wide open; and (4) by a pressure drop across the substrate essentially equal to the draft just above the substrate (and hence essentially zero draft [actually slightly positive] below the substrate--and thus the smoke spillage there (Figure 2)).

The following are some of the notable results of the plugging tests:

- Glass fibers from packing tape can become stuck on the leading face of the monolith and contribute to plugging principally by increasing the surface area for soot accretion.
- Both newspaper char and newspaper ash (Figures 3 and 4) can contribute to plugging at the leading face.
- Plugging is not just a problem at the leading face--substantial material accumulated inside the cells (Figures 5 and 6).
- Some deposits adhere very loosely (Figure 7).
- Seasoned (dry) wood is not less likely to result in plugging.
- Slight plugging can occur on the leading edge of an active catalyzed monolith (Figure 8).
- Substantial plugging can occur even when the average smoke temperature is rather high (> 300° C.).

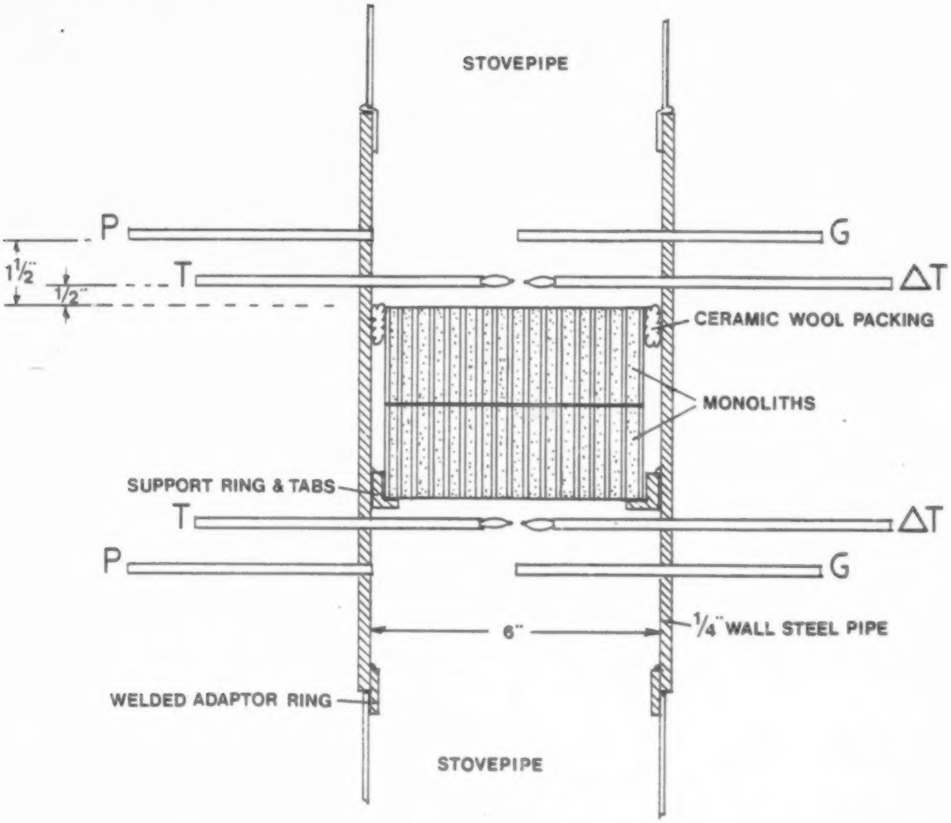

STOVEPIPE
P
G
1½"
T
½"
ΔT
CERAMIC WOOL PACKING
MONOLITHS
SUPPORT RING & TABS
T
ΔT
P
G
6"
¼" WALL STEEL PIPE
WELDED ADAPTOR RING
STOVEPIPE

Figure 1. Detailed experimental arrangement around the catalyst, for Project No. 1

G: Gas sampling tubes for O_2 and CO_2 analysis.
P: Pressure taps, for draft and pressure drop measurements.
T: Thermocouples
ΔT: A second set of thermocouple junctions for direct measurement of the temperature difference above and below the catalyst.

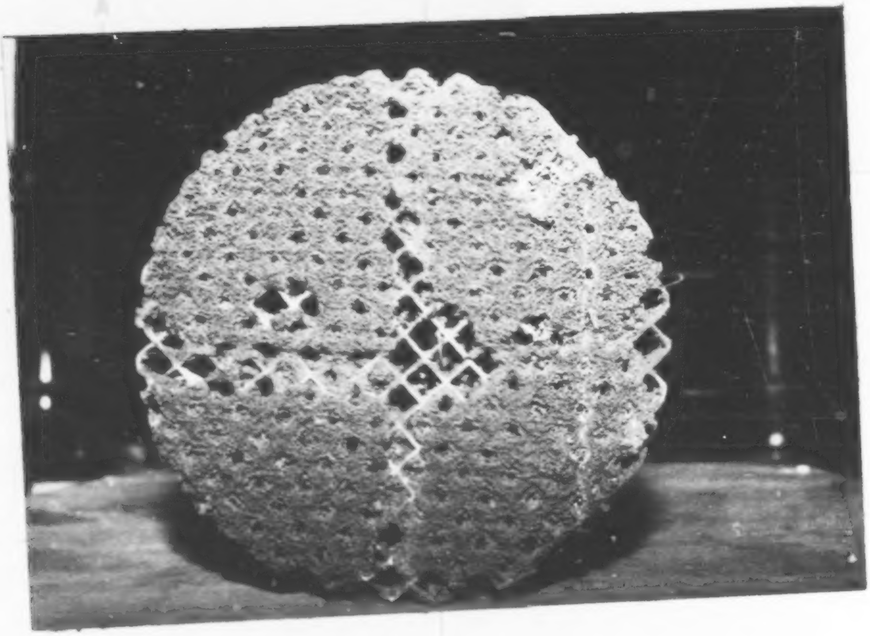


Figure 2. A substantially plugged uncatalyzed substrate.

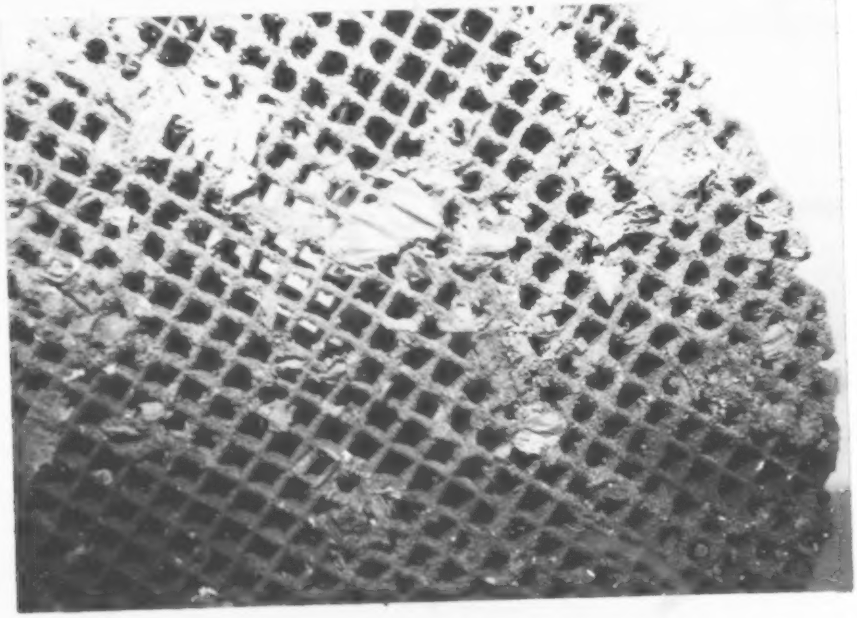


Figure 3. Newspaper char adhering to the leading face of a substrate.

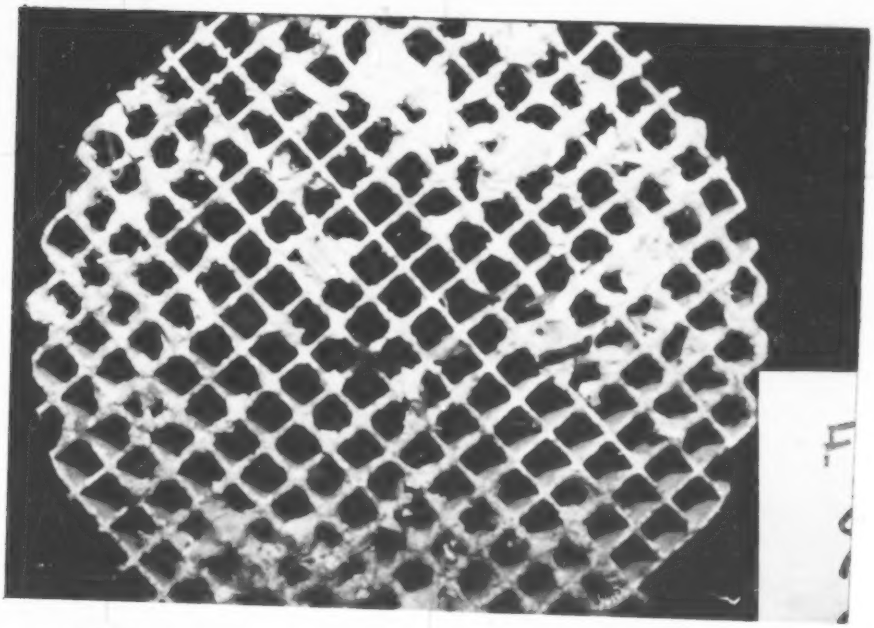


Figure 4. Newspaper ash adhering to the leading face of a substance.

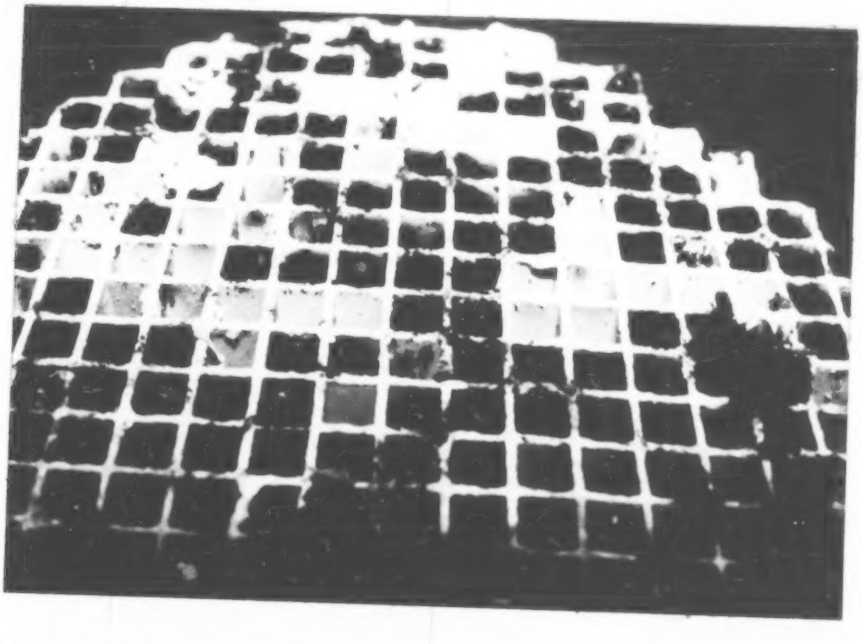


Figure 5. Non-uniform deposits. Some cells are clean, others are moderately obstructed with deposits.

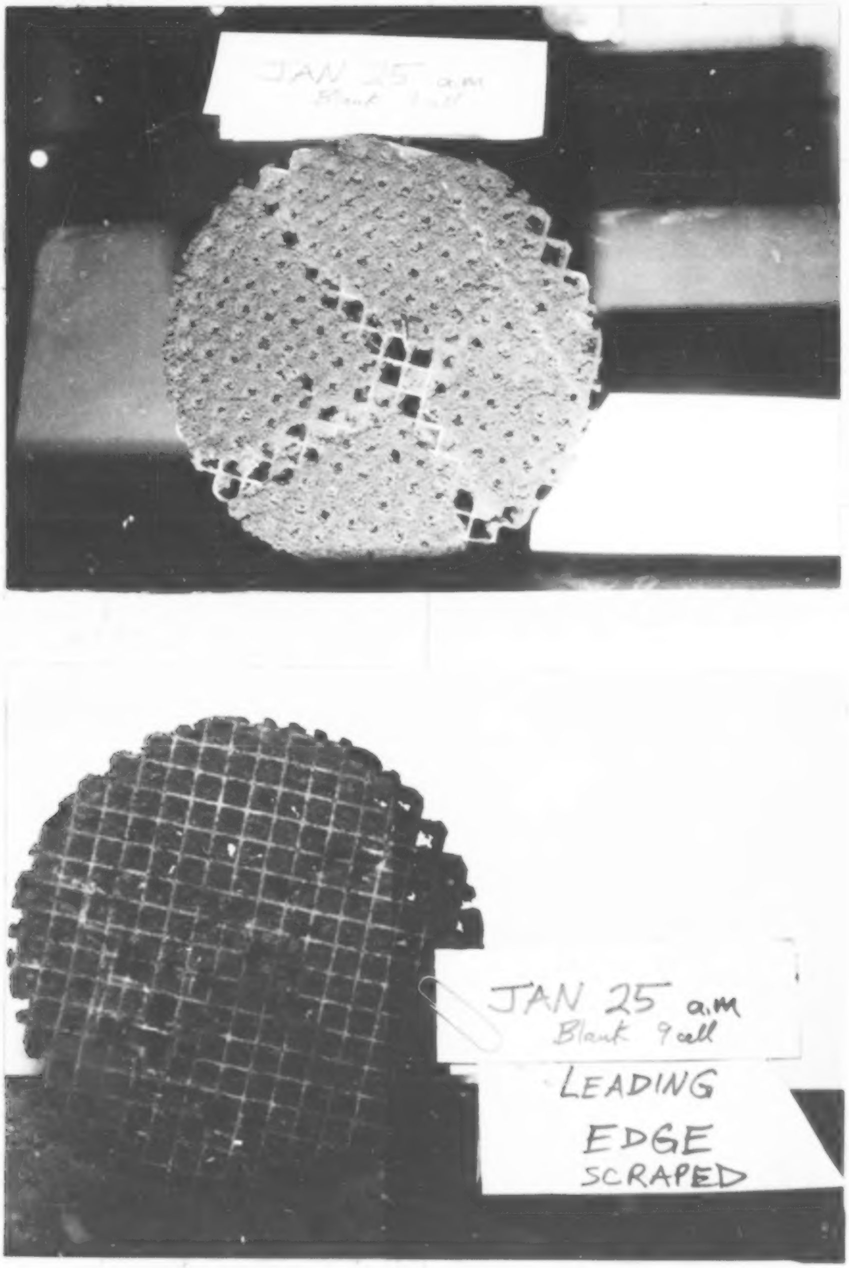

JAN 25 a.m
Blank 9 cell
JAN 25 a.m
Blank 9cell
LEADING
EDGE
SCRAPED

Figure 6. The leading face of a substrate before and after being scraped clean. Plugging does not occur just at the leading face.

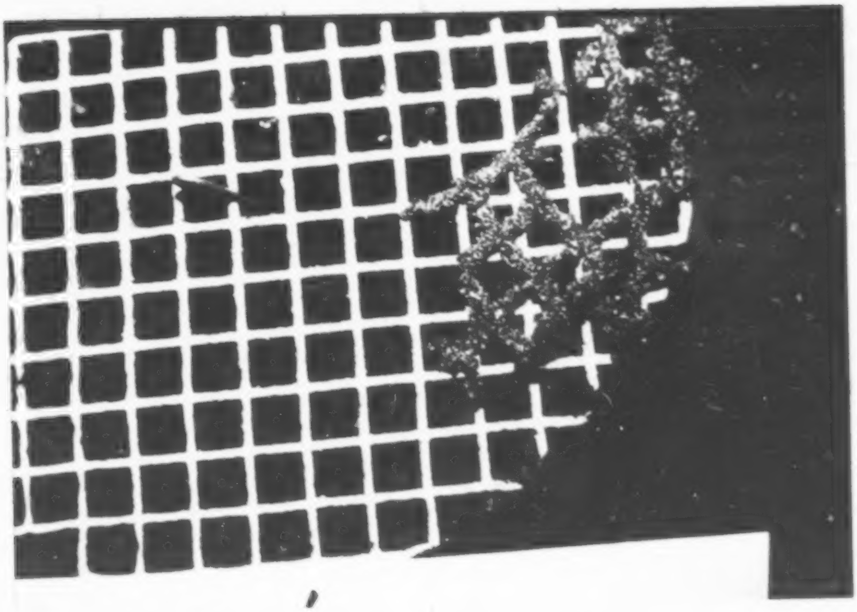


Figure 7. Some deposits are only on the leading face and adhere very loosely.

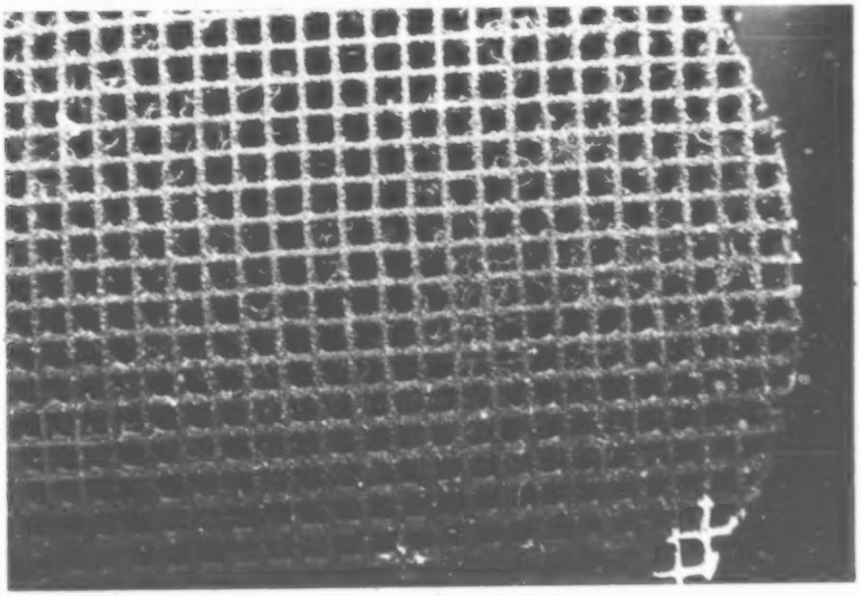


Figure 8. The leading edge of a catalyzed substrate. Deposits are not a problem associated only with catalyzed substrates.

That plugging can occur in a worst-case situation is really no surprise. How likely and in how much time is plugging likely in the field? This is the key question and only field testing can answer it. The potential danger depends on how fast the blockage occurs.

The plugging potential must be taken into account when engineering catalytic systems. Some approaches which can help are:

- Locating the catalyst close to the wood fire to increase the temperature;
- Providing a bypass so that even if the catalyst does become plugged the smoke still has access to the chimney;
- Using a relatively open substrate structure;
- Including advice and cautions in the instructions to the user.

I do not see plugging as a serious impediment to catalytic combustion in wood stoves, but it deserves some careful engineering effort.

High Temperatures

When a catalyst is working properly, the heat released can be very large--as much as 50 percent of the heat is released in the wood fire itself. This follows from the fact that combustion efficiencies can be as low as 65 to 70 per cent in a smoldering wood fire. Thus the temperatures at and downstream from the catalyst can be very high.

Without proper engineering, high temperatures can cause premature failure of parts of the heating system. The generally accepted safety standards for wood heating systems and their chimneys (UL 1482, UL 737, UL 103, UL 127 and UL 462) contain temperature limitations of various materials which are intended to insure reasonable durability. In addition, the standards for stoves and fireplaces have limitations on flue gas temperatures which are intended to assure consistency with the chimney standard: use of the appliances should not result in flue gas temperatures which exceed the test conditions in the standard for solid-fuel chimneys.

The effort to achieve maximum temperatures above the catalyst involved the use of three stoves--a Riteway Model 37, a Fisher Baby Bear and a Petit Godin Model 3721. Wide ranges of smoke density, temperature and velocity were explored by varying the air inlet setting and the fuel load size, piece size, species and moisture content. Since effective operation of a catalytic combustion system requires adequate oxygen, each stove installation was modified so that a variable amount of air (or even pure oxygen) could be added to the smoke below the catalyst. The catalyst was always located in the chimney connector close to the stove for these tests.

Flue gas temperatures were measured as prescribed in related UL standards. Measurement locations included 1/2 inch below the catalyst, 1/2 inch above the catalyst and at 2-foot intervals for 6 feet above the catalyst. Maximum metal temperatures (of the monolith containment pipe and of the connecting stovepipe) were measured using Templestik temperature-sensitive crayons spaced at 50-degree Fahrenheit intervals.

Flue gas temperature measurement is complicated by the facts that

- kinetic and radiant temperatures are usually not the same, and
- kinetic and radiant temperatures are both spatially nonuniform.

All flue gas temperatures reported in this paper were measured using a bare thermocouple located in the center of the flue. Radiation from the operating catalyst tends to make nearby thermocouples hotter than the flue gas, but heat loss from a thermocouple by radiation to the cooler flue wall tends to make the junction cooler than the gas's kinetic temperature.

Thus the measured temperatures reported here are most likely not the actual kinetic temperatures of the flue gas. However bare thermocouples give easily reproducible measurements and, most important in the present context, the temperature limits specified in the UL standards are based on bare thermocouples as probes.

There is not a unique set of conditions for obtaining the highest temperatures (flue gas and surface) with catalytic combustion. One would generally expect, other things being equal, that temperatures above the catalyst would be increased by increasing the smoke density or oxygen concentration depending on which is limiting, and by increasing the temperature of the flue gas entering the catalyst. In fact, these three variables (smoke density, oxygen concentration, and temperature) are somewhat interdependent.

The optimum ratio for smoke and oxygen concentrations is of course stochiometric--just enough oxygen to fully oxidize the smoke. Excess smoke cannot be burned and excess air dilutes the mixture. However, wood fires do not always respond as one might expect. Under many circumstances, letting in more combustion air will decrease the oxygen concentration in the smoke above the fire. And although a sudden decrease in the combustion air supply will momentarily decrease the oxygen concentration, the longer term effect can be to increase the oxygen concentration in the smoke. Adding secondary air can help, but it must be done carefully.

The flue gas temperature below the catalyst is also not an independent variable. Given a concentrated and stochiometric mixture of smoke and oxygen, raising its temperature below the catalyst will raise the temperature above the catalyst only for temperatures below a critical range. As the flue gas temperature is raised, there comes a point (at roughly 500 to 700° C.) at which the mixture is above its ignition temperature and so is burning already. In this case the catalyst is not as critical (although it can help); the temperature above the catalyst is not highly sensitive to the presence of the catalyst or the temperature of the entering gases. Stated another way, high flue gas temperatures decrease the smoke and oxygen concentrations by stimulating ordinary combustion.

Our experimental observations (Table 1) were consistent with these expec-

Circumstances	T below (°C)	T above (°C)	ΔT (Centi-grade°)	O_2below (% by volume)	O_2above (% by volume)	Velocity (m/sec)
Maximum observed ΔT	300	820	520	12	2	1.8
Maximum observed T above	400	850	450	10.5	0	1.3
Maximum observed T below	820	650	-170	0	0	1.0
Representative	300	760	460	12	5	1.8
Representative	220	370	150	10.5	8	0.3
Representative	270	540	260	4	0	1.1
Representative	400	350	-30	0	0	0.9

Table 1. Some results of catalytic combustion using 6 inches (in either 2 or 4 segments) of monolith with 9 cells per square inch. Data is approximate (±10 percent) due to the time variability of wood fires and the fact that not all data, particularly the two oxygen readings, were obtained simultaneously.

tations. When the smoke was dense and ample oxygen was available and the temperature was roughly 200 to 400° C., the catalyst worked effectively, raising the flue gas temperature by 200 to 500 Centigrade degrees to a value of 600 to 800° C. Raising the temperature of the smoke below the catalyst still higher did not have a large effect on the temperature above the catalyst. In fact, for input temperatures above about 600° C., we often observed a temperature drop through the catalyst, suggesting that combustion was already complete and heat was being lost.

The highest flue gas temperatures seen during our experiments were about 850° C. (1560° F.) above the catalyst and 820° C. (1500° F.) just below. Higher temperatures are certainly possible, especially for catalysts placed closer to the appliance's combustion chamber since flames, catalytically assisted or not, can be hotter than the temperatures we observed.

Do such temperatures pose either a safety hazard, or a hurdle to overcome in obtaining UL listing of catalytic combustion equipment? The answer is "No." These temperatures are not hazardous in a properly engineered system.

UL 1482 has two flue gas temperature limitations applying to different portions of the firing tests. During the radiant and brand fire tests, "the temperature of the flue gases entering the chimney shall not exceed 1000° F. (538° C.) except that the temperature of the flue gases may exceed 1000° F. (538° C.) but not exceed 1400° F. (760° C.) for a cumulative period not exceeding 12-1/2 percent of the test duration."[4] During the flash fire test, "the temperature of the flue gases entering the chimney shall not exceed 1400° F. (760° C.) except that the temperature of the flue gases may exceed 1400° F. (760° C.) but not exceed 1700° F. (927° C.) for a cumulative period not exceeding 10 minutes during the duration of the test."[5] These temperatures are as measured only within 6 inches of the beginning of the chimney. Thus considerably higher temperatures further upstream (below) in the stovepipe are permitted by UL 1482. Thus high flue gas temperaures do not seem to be a problem even with afterburners located above the appliance as long as there are a few feet of stovepipe between the afterburner and the chimney.

UL standards have temperature limitations on some materials used in stove and chimney construction. Most of these limitations relate to safety through durability. There are not now any limitations on temperatures of refractory and ceramic materials. The maximum temperature allowed for low carbon steel less than 1/4 inch thick is 517° C. (930° F.) above ambient. The highest metal temperature we observed was between 427 and 454° C. (800 and 850° F.); the location was the lowest portion of stovepipe just above the catalyst containment pipe, about 4 inches above the top of the catalyst. Higher temperatures could certainly be achieved, but I see no problems since materials with higher temperature limits could be used (such as stainless steel).

In terms of maximum achievable temperatures, catalytic combustion is really no different from ordinary combustion. In both cases combustion can be nearly complete, and when it is, both flue gas and material temperatures are determined by the balance between the rates of heat evolution and heat transport and loss, and these rates are not particularly affected by how combustion is achieved. This is not to say that dealing with high temperatures is trivial, but that equally high temperatures must be dealt with in most woodburning systems whether catalytic or not.

Flow Resistance

Catalysis requires large surface areas. If a catalytic combuster is to be relatively compact, this then implies some flow resistance. If the flow resistance is not taken into account in designing catalytic systems, smoke spillage may result and high peak powers may be difficult to achieve.

During all plugging and high temperature tests, smoke spillage was noted when present. The catalyst was located in the stovepipe connector 1 to 3 feet from the stove. The catalyst geometries included 9 and 25 cells per square inch, total lengths of 3 to 6 inches in 1 to 4 stacked pieces. Ceramic wool was used to seal the monoliths in the pipe--there was no leakage around the outside of the monoliths and there was no other bypass.

Some smoke spillage was observed (with clean catalysts), particularly before the catalyst started working and/or when the loading or ash door was left open to try to heat up the system more quickly. The smoke came through leaks near the tops of the stoves and/or through stovepipe joints below the catalyst. With a stove door open, the pressure drop across the catalyst was essentially equal to the draft measured just above the catalyst (typically 0.04 to 0.07 inches of water). Spillage was rarely observed when the catalyst was operating well.

A quantitative measurement was made of flow resistance as a function of velocity for 2 stacked 3-inch lengths of monolith with 9 cells per square inch (Figure 9). Air was used and the two sets of cells were not aligned with each other. (Other measurements indicated that the degree of alignment is a detectable but not critical factor.) Typical flue gas flows are 10 to 40 grams per second, or roughly 1/2 to 2 meters per second at standard temperature and pressure. With air in the pipe these velocities give pressure drops of about 0.01 to 0.07 inches of water. With hot smoke instead of air, the pressure drops would be the same order of magnitude and are thus consistent with the pressure drop and smoke spillage observed during stove operation.

Because of flow resistance in the honeycomb geometries tested, these substrates are not suitable for use in fireplaces, fireplace stoves or inserts if the catalyst is to be useful during open-door operation. Other more free-flowing designs are possible but are likely to be less compact. In stoves, furnaces and boilers, possible spillage during fuel loading can be eliminated by a bypass which is automatically opened when the door is opened.

Overall, flow resistance is not a serious problem but it must be addressed in well engineered systems.

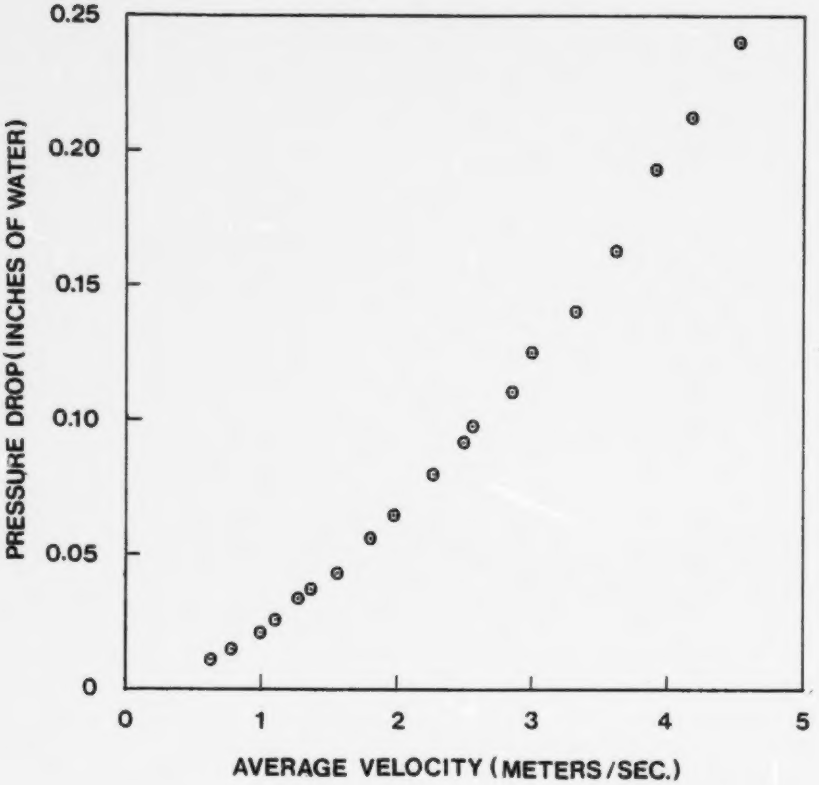


Figure 9. Measured pressure drop for 60 to 70° F. air at an ambient pressure of about 650 mm Hg flowing through 2 stacked 3-inch lengths of catalyzed monolith with 9 cells per square inch. The two pieces were about 45 degrees out of parallel alignment with each other.

Project No. 2

THERMAL PERFORMANCE TESTS OF A CATALYTIC STOVE

Not much data has been available concerning the performance advantage of catalytically assisted combustion in stoves. Expectations have been high. Many stoves operate with combustion efficiencies of 70 to 90 percent--i.e., with 10 to 30 percent of the fuel's energy leaving the system unburned as smoke. Even if a catalytic system burned only half of this material and if only half of the additional heat were recovered, the overall energy efficiency of the heating system would increase by about 5 to 15 percent (2.5 to 7.5 percentage points) assuming a 50 percent overall energy efficiency without the catalyst. It is likely that in a well designed system performance improvements could be higher than in this estimate.

Experimental Set-up and Procedures

The stove chosen for this test was not a production catalytic stove but a modified Riteway Model 37. Although it would be interesting and useful to test production stoves, in this case it was thought more useful to test a configuration closer to one which Corning Glass Works had been monitoring.

The objective was to obtain some performance numbers for a simple, straightforward design with and without a catalyst. The design of the stove/catalyst system was not optimized in any sense (Figure 10). To the extent that the catalyst is placed directly over the fire, the design is similar to production catalytic stoves currently available, but with regard to heat transfer downstream of the catalysts, there may well be differences. There is no necessary correspondence between the results for the modified Riteway used in this testing and production catalytic stoves, although some correlation is to be expected.

The catalyst itself was 3 inches long, a little less than 6 inches in diameter, and had 16 cells per square inch. The catalyzed substrate was supplied by Corning Glass Works as part of contract work for Corning for the purpose of conducting the tests described here.

The catalyst was mounted in 6-inch stovepipe which in turn was installed through a hole cut in the stove top. The bottom of the catalyst was over the fire, flush with the end of the stovepipe, and 3 inches below the top of the stove. The annular space between the catalyst and the stovepipe was not sealed.

The manual bypass for the system was the normal bypass in the Riteway stove. The stovepipe from the stove's collar and from the catalyst joined above the stove and vented into a common chimney--an 8" inner diameter double wall insulated chimney which terminated 16 feet above the floor on which the stove stood. The usual flow pattern of the Riteway was disabled by blocking

191

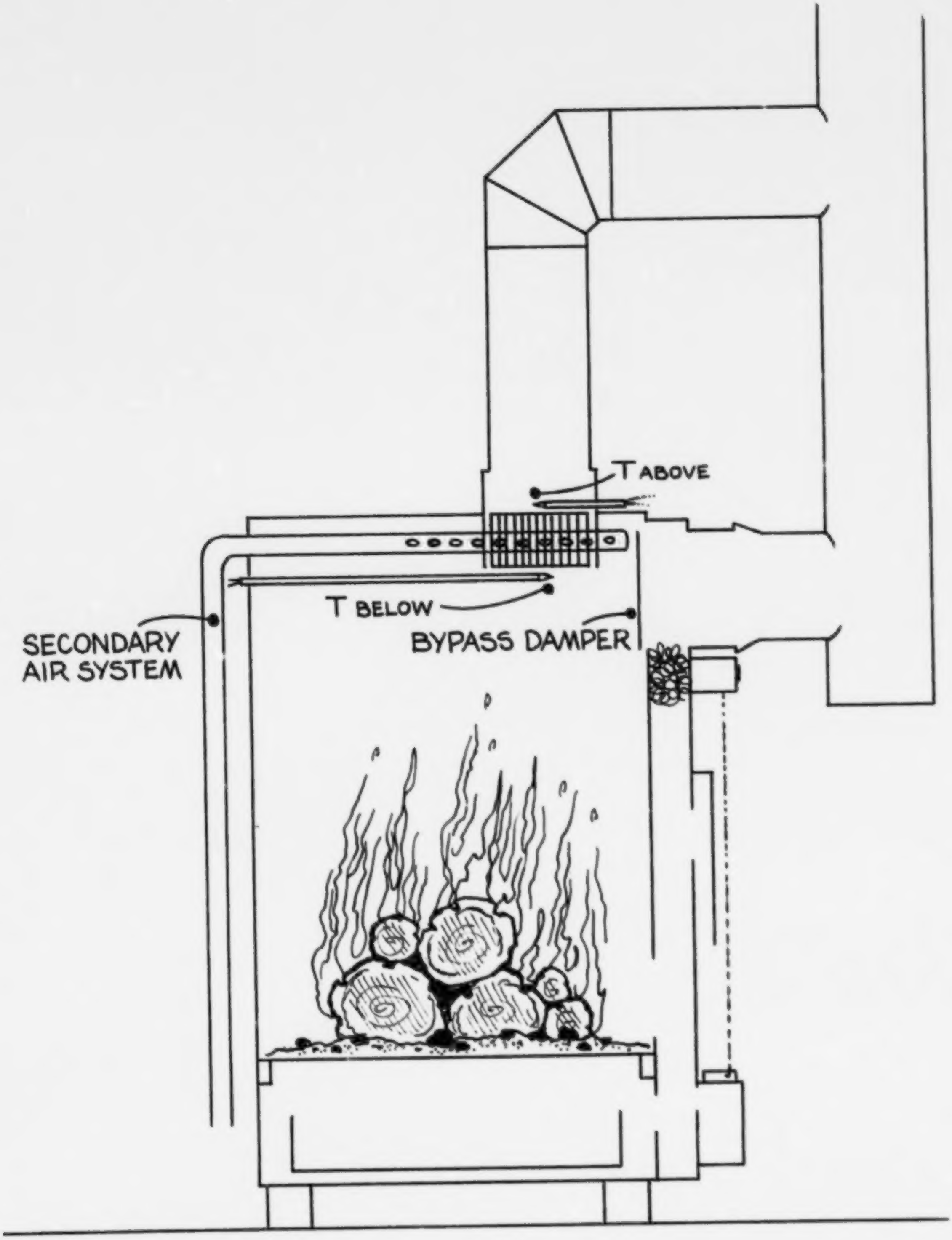

T ABOVE
T BELOW
SECONDARY AIR SYSTEM
BYPASS DAMPER

Figure 10. The modified Riteway 37 stove used in measuring the change in energy efficiency due to a catalytic combuster, Project No. 2.

the flue channel which runs up the outside of the stove. The amount of hot, exposed (uninsulated) stovepipe when the catalyst was in use was 4 feet.

Secondary air was admitted through small holes in two 5/8-inch inner diameter pipes passing through the stove from side to side at the top of the stove, one each on either side of the catalyst. This system admitted enough oxygen to maintain a non-zero oxygen concentration above the catalyst at all but a fraction of a percent of the time.

The test method was room calorimetry combined with a determination of flue heat loss--the standard method used by Shelton Energy Research for the last five years. This combination yields more information than any one of the standard methods by itself. The information includes continuous heat output curves over time, overall energy efficiency, combustion efficiency and heat transfer efficiency.

The calorimeter room measures the heat output of the appliance directly and continuously. Our room uses once-through air. Measurement of the air's flow rate and temperature rise yields the power output from the appliance.

Aside from the relatively small effect of heat storage in the room's structure, the time response of the system is less than half a minute. The system's sensitivity on this time scale is limited only by temperature noise in the input air, which, after passing through a massive rock-bed temperature averager, is about 0.01° C. This corresponds to about a 10-watt signal, and indeed the heat output of a 15-watt lightbulb in the calorimeter room is easily detectable, as is the metabolic heat output of human bodies (Figure 11).

The sensible heat loss up the flue is determined by measuring the temperature and the velocity of the flue gases where they leave the calorimeter room. Both parameters are non-uniform across the flue. Mass-flow weighted averages are required. We measure temperature averaged over 8 points in the flue. Extensive insulation both upstream and downstream from the measurement location make radiation shielding unnecessary. The sensor for velocity measurements is essentially a Pitot tube array which is claimed by the manufacturer to yield as its output the square of the average of the square roots of the pressure-difference signals. We actually calibrate the system over the range of flows and temperatures encountered in solid-fuel appliance testing. The transducer is a Datametrics capacitive manometer with a sensitivity of better than 10^{-5} Torr. Heat capacity of the flue gases is calculated from measured values of the temperature and a partial flue gas analysis. The sensible heat loss up the stack is then given by $\int \dot{M} C \Delta T = \int A f \sqrt{2 \Delta P \frac{MWP}{RT}}\, C \Delta T \, dt$

where $\dot{M}$ = mass flow
C = specific heat
ΔT = flue-gas temperature minus ambient temperature
A = cross sectional area of flue
f = calibration factor for velocity measurement (value is approximately 1)
ΔP = pressure difference from Pitot tube array
MW = average molecular weight of flue gas
R = gas constant
T = absolute temperature
P = atmospheric pressure

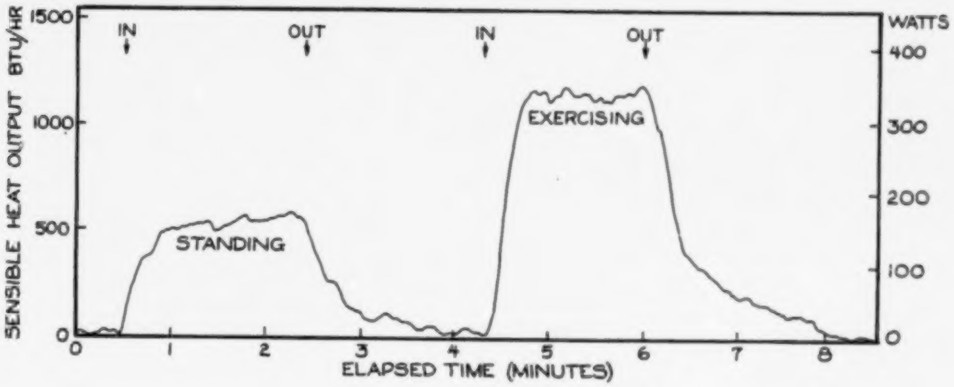


Figure 11. The body heat output of a resting and exercising adult measured in a Shelton Energy Research calorimeter room.

The chemical energy loss up the stack can then be computed using energy conservation. The latent heat loss is calculated theoretically assuming complete combustion. The chemical energy loss is the wood energy input minus the useful heat output (measured by calorimeter room), the sensible heat stack loss and the latent stack loss. Combustion and heat transfer efficiencies can then be calculated using the following definitions:

$$\text{Combustion efficiency} = \frac{\text{heat energy (sensible plus latent) generated in combustion}}{\text{wood energy input}}$$

$$\text{Heat transfer efficiency} = \frac{\text{useful heat energy output}}{\text{heat energy generated in combustion}}$$

$$\text{Overall energy efficiency} = \frac{\text{useful heat energy output}}{\text{wood energy input}}$$

$$= (\text{combustion efficiency}) \times (\text{heat transfer efficiency})$$

The variable and unknown energy release rate from the wood makes it impossible by this or any other standard test method to obtain instantaneous energy efficiencies.[2, 6] All three energy efficiencies are thus averages over at least one complete burn cycle. Our tests typically last 6 to 12 hours. They are intentionally long in order to obtain results characteristic of typical operation.

The fuel used was Douglas fir with a moisture content of about 18 percent. The main fuel load consisted of 4x4's. The stacking geometry was as in firebrands; 2 long pieces 1 inch apart as the bottom layer, four shorter pieces perpendicular to the long pieces and also 1 inch apart from each other, and then 2 more long pieces for the top layer. Piece lengths were all 4 inches shorter than the corresponding internal dimension of the stove. The total mass of the kindling and the 8 4x4's was typically between 22 and 25 kg.

Standard firebrands (crossed layers of 3/4 x 3/4" zero moisture content Douglas fir) are rarely used in our laboratory because use of such an unrealistic fuel significantly distorts performance, and not just by shifting the efficiency of all appliances up or down but by changing the relative efficiencies of different appliances.[2, 6]

As is the usual convention in the United States, we take as the wood's energy content its higher or gross heating value, which includes the latent heat of the water vapor from combustion. The heating value of Douglas fir varies from sample to sample more than in the case of some other species. Thus we do our own bomb calorimetry on representative samples of the particular wood supply used in our testing. The value for this series of tests was 2.03×10^7 Joules per kilogram (8730 Btu per pound) at zero moisture content.

The tests start and end with the stove at room temperature. The fire is started with newspaper and kindling (also Douglas fir) with the air inlet full open and the bypass damper open. After about 20 minutes the main fuel load was added and the air inlet set to the desired value for the duration of the test. After about 15 more minutes the bypass was closed. No adjustments were made for the remainder of the test.

These starting procedures were intended to assure that the catalyst was started off working properly by establishing a strong hot fire before closing the bypass and restricting the air supply. No problems were encountered obtaining light off of the catalyst. The catalyst was often functioning during the kindling phase, before the bypass was closed.

All tests consisted of pairs with and without the catalyst in place. Tests were conducted at 3 power outputs. Maximum power was defined as the power obtained with the catalyst in place and the air inlet wide open. For the corresponding test without the catalyst, it was found that a slightly restricted air supply was necessary to achieve the same power output. The other two test pairs were conducted with smaller air inlet settings. The endpoints for determining the average power were the time the main fuel load was added, and the time when, in the opinion of the operator, the fire was ready for another fuel load, i.e., when the fuel was reduced to a healthy bed of glowing coals. This is admittedly subjective but since average power is not a critical parameter in the analysis or interpretation of the data, the procedure needs little quantitative justification.

Results

Three typical power curves are shown in Figure 12. The initial spike is from the kindling load. After the bypass was shut and air inlet set, the curves represent the natural variations of the fire itself.

The overall energy efficiencies for all tests conducted thus far are plotted in Figure 13. All tests were repeated twice, both with and without the catalyst. The average difference in energy efficiency within these repetitions is less than one percentage point. This consistency requires, among other things, uniform average moisture content from test to test within 1 to 2 percentage points. This we achieve by storing the fuel for a long time (months) in a humidity controlled room.

The effect of the catalyst is clear and substantial. At the two lower power outputs, the increase in overall energy efficiency is about 9 percentage points, or about 17 to 18 percent. At the highest power output, the effect was 6 percent or 3 percentage points. It is to be expected that a catalyst is less effective at higher power outputs since combustion tends to be more complete at high than at low outputs without catalytic assistance.

The measured temperatures above and below the catalyst are consistent with this interpretation (Figure 14). The temperatures were measured (as indicated in Figures 1 and 10) with unshielded junctions and thus do not represent the kinetic temperature of the gases. However the sign and magnitude of the temperature difference is related to catalytic combustion--a substantial temperature rise of the flue gases as they pass through the catalyst indicates combustion. As evident in Figure 14, the catalyst was inducing considerably more combustion during the low power than during the high power burn.

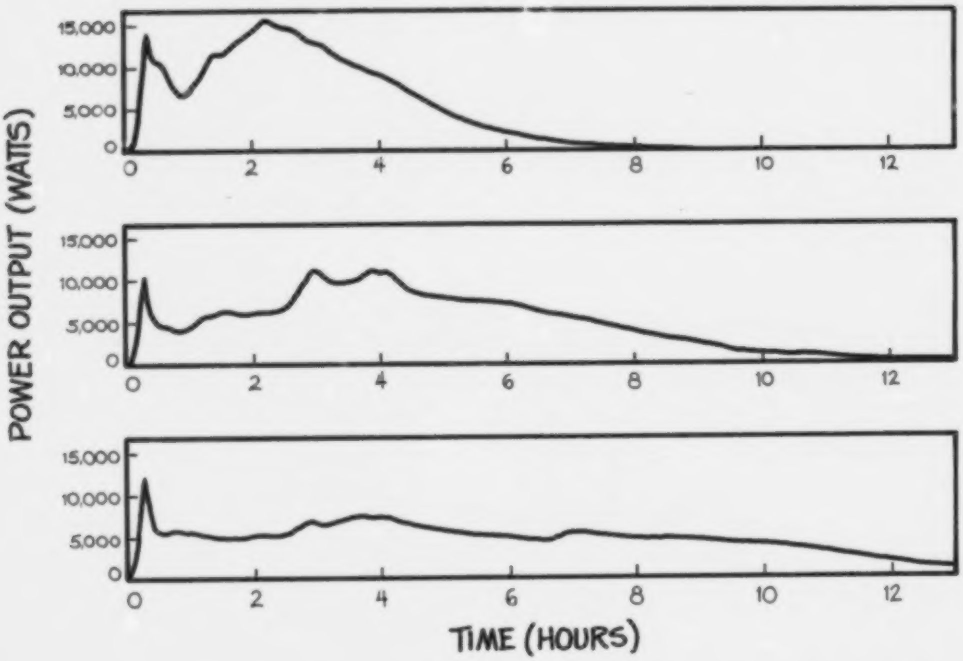


Figure 12. Typical power output curves at the three powers tested. The shapes of the curves were similar with and without the catalyst, but of slightly longer duration and with a slightly larger integral when the catalyst was present.

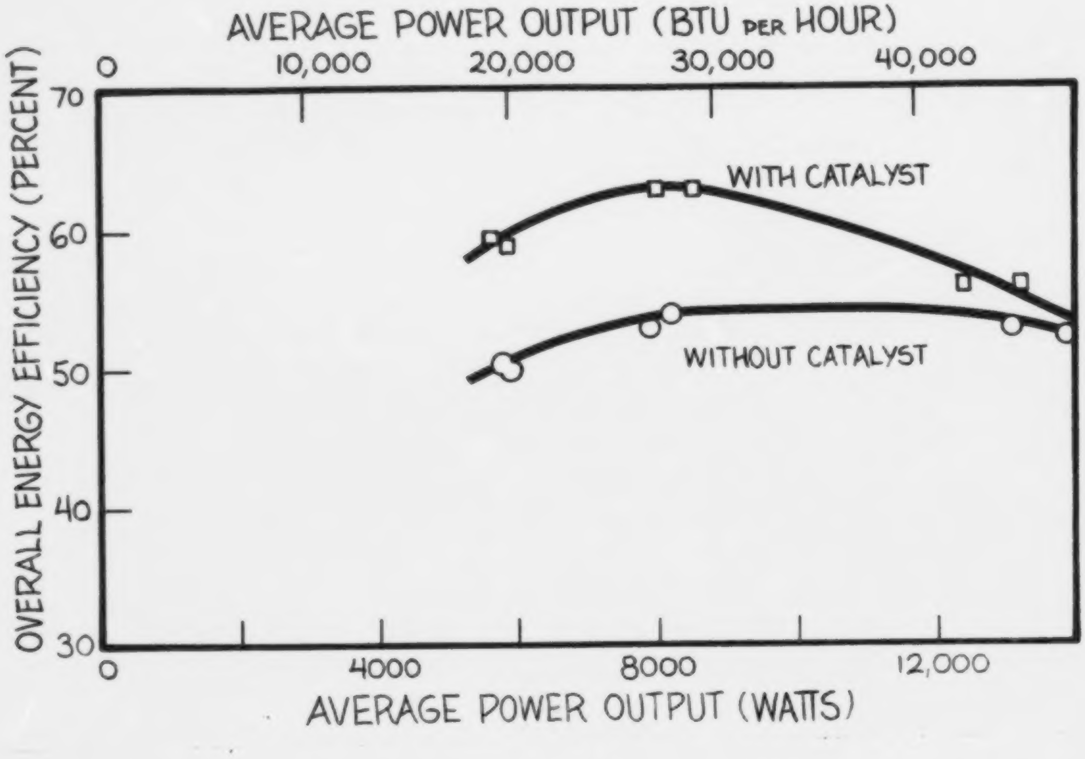


Figure 13. Overall energy efficiency of the modified Riteway 37 with and without the catalyst.

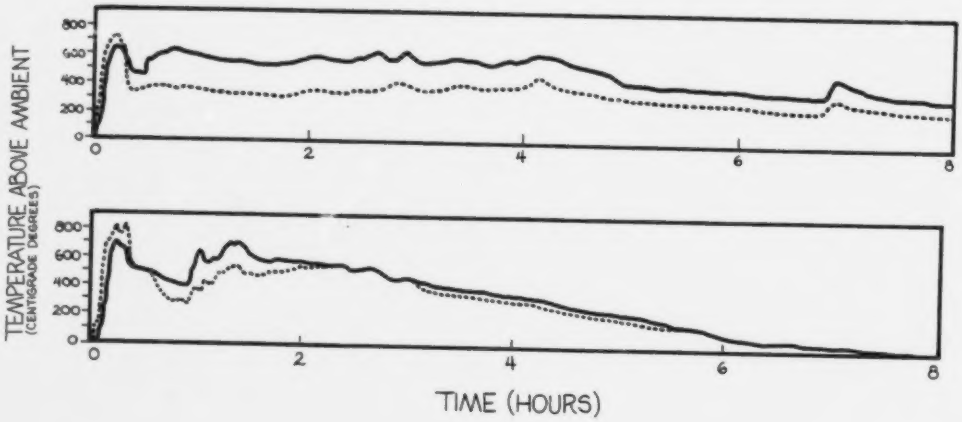


Figure 14. Temperatures above (solid curve) and below (dashed curve) the catalyst during a low-power test (upper graph) and a high-power test (lower graph).

This work was still in progress at the time this paper was written. Final results for combustion and heat transfer efficiencies were not yet available. However it appears that it is not only combustion which is increased by the catalyst in this particular stove but that heat transfer efficiency is also improved. This would be consistent with preliminary and unpublished results from Shelton Energy Research.

CONCLUSIONS

Catalytically assisted combustion in residential wood-fuel heating appliances has great potential for reducing creosote, reducing emissions and increasing overall energy efficiency. I am optimistic about the success of catalytic combustion in wood stoves. It is one of very few truly innovative developments. But I believe current designs are by no means optimized. Some areas deserving of effort are downstream heat transfer, plugging and catalyst durability. Plugging and durability not only need laboratory research but also field testing. The fuels and additives people use, and how they operate the appliances, can have substantial influence on plugging and durability.

FOOTNOTES

1. "Creosote" is used here to mean any combustible material, solid or liquid, deposited in the chimney, the connector or the appliance, whose origin was products of incomplete combustion (including vapors, tar, mist and soot.)

2. Jay W. Shelton, et al., "Woodstove Testing Methods and Some Preliminary Experimental Results," ASHRAE Transactions 48 pt. 1, pp. 388-404 (1978).

3. D. F. Dyer, T. T. Maxwell, G. Maples et al., "Improving the Efficiency, Safety, and Utility of Wood Burning Units," Quarterly Reports WB-1 through WB-7, DOE Contract No. DE-A504-77ET 11288 (formerly ERDA EC77505552), Department of Mechanical Engineering, Auburn University (1977-79).

4. Paragraphs 12.6 and 13.12 of UL 1482, First Edition (May, 1979).

5. Ibid., paragraph 14.9.

6. A more up-to-date discussion of various test methods (than in the reference in footnote 2) will be available in July, 1981, from Shelton Energy Research, P.O. Box 5235, Santa Fe, NM 87502.

MEASUREMENTS OF CHEMICAL CHANGES DUE TO CATALYSIS OF WOODSTOVE EFFLUENT

by: Dr. Dennis R. Jaasma
Department of Mechanical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

ABSTRACT

Pollutant emissions from woodstoves are responsible for chimney fires and may also have a serious effect on human health. Since woodstove stack emissions contain negligible amounts of sulfur oxides, nitrogen oxides, and ash, all of the pollutants of concern are combustibles and can be eliminated by oxidation to CO_2 and H_2O. Use of a catalyst to encourage the oxidation process is an attractive idea from both energy conservation and air pollution standpoints. Potential problems with use of a catalyst to reduce emissions to acceptable levels include fouling before operating temperature is reached, production of secondary products such as ammonia or hydrogen cyanide during fuel-rich operation, and a draft requirement in excess of that required by conventional chimneys. The recent commercial debut of a stove containing a monolithic catalyst indicates that start-up and natural draft operation can be achieved, but details on the chemical nature of the effluent are not yet available. Experiments to characterize the chemical and physical transformations of woodstove effluent as it passes over a noble metal catalyst are now under way at the VPI Solid Fuels Research Laboratory. Preliminary results are presented and discussed.

INTRODUCTION

The renewed interest in wood as an energy source for residential heating has brought with it both benefits and costs. On the benefit side of the ledger are several items: economic advantage to the individual who burns wood and to people who pay less for oil due to reduced demand for oil; the reduction of our dependence on non-renewable energy resources; and the stimulation of the domestic economy as evidenced by the growth of the stove, chainsaw, and firewood industries. Some of the costs of woodburning are obvious: loss of life and property due to fire, and accidents in the harvesting and processing of firewood. Some are somewhat less obvious--one such cost being the degradation of air quality. Due to the different geographical and meteorological features of the areas where wood is burned, this degradation is severe in some areas and unnoticable in others. Perhaps more important than the readily perceived consequences of air degradation

TYPING GUIDE SHEET

(reduced visibility, oder, soiling) are the long-range health effects which may result. DeAngelis, et al. (1) have performed the most extensive study of woodstove and fireplace pollutant emissions, and found large amounts (relative to other combustion systems) of particulate matter, carbon monoxide, and polycyclic organic matter (POM). To put this in perspective, Fig. 1 shows the relative amounts of several pollutants for the same amount of delivered heat from different home heating systems. The particulate and POM emissions are of concern because many of the chemicals classified as POM are known animal and/or human carcinogens. Thus, it is possible that increases in lung diseases may result from use of wood as a residential heating fuel. In addition, it may be years before these effects are noticed, at which time much irreversible damage may have been done.

The possible health effects of wood emissions are not the only reasons for wanting to develop cleaner-burning stoves. There are efficiency (economy) reasons as well. In the case of residential woodstoves, virtually all the air pollutants are combustibles. This is because the ash stays in the stove and the combustion process produces negligible amounts of noncombustible gaseous pollutants such as nitrogen oxides or sulfur oxides. The accumulation of these combustibles (in the form of creosote) is the cause of chimney fires, these fires being dramatic evidence of the heating value of the emissions. Thus, the pollutant emissions represent a chemical energy loss, lowering the efficiency of the stove. The magnitude of this loss is frequently cited as 5 to 30% of the fuel's heating value, which means that there is the potential to reduce fuel requirements by around 10%, assuming you can burn up all the combustibles and maintain a 50% heat transfer efficiency. A household which normally spends $400 for four cords of wood each heating season would thus have a savings of $40 per year. Burn-up of these combustibles would also eliminate the need for chimney cleaning, saving (approximately) an additional $30 per year and bringing the annual savings to perhaps $70.

These considerations indicate that there would be a market for a device which could be added onto or built into a stove, burn up the pollutants, and deliver the heat to the dwelling. A catalytic convertor is the obvious candidate for this task, and the recent development by Corning of an in-stove, monolithic catalyst holds great promise for making this a reality for future stoves. There are, however, possible drawbacks to use of a catalyst. A catalyst can, under certain conditions, cause the formation of secondary products. These secondary products are quite toxic and include hydrogen cyanide, ammonia, and other nitrogen-containing compounds. Such products are observed when catalyst-equipped automobiles are operated under slightly rich (air deficient) conditions (2). Because woodstoves have the potential to be operated very rich compared to automobiles, there is the possibility that secondary products could be produced in much larger quantities than in automotive applications. Extremely fuel-rich operation of a catalyst-equipped stove will likely coat the catalyst with particulate and prevent secondaries from being formed. However, there may be non-clogging, fuel-rich operating conditions which are desirable from the standpoint of controlling heat delivery rate but undesirable regarding formation of secondaries. It is probably possible to design a new stove which does not

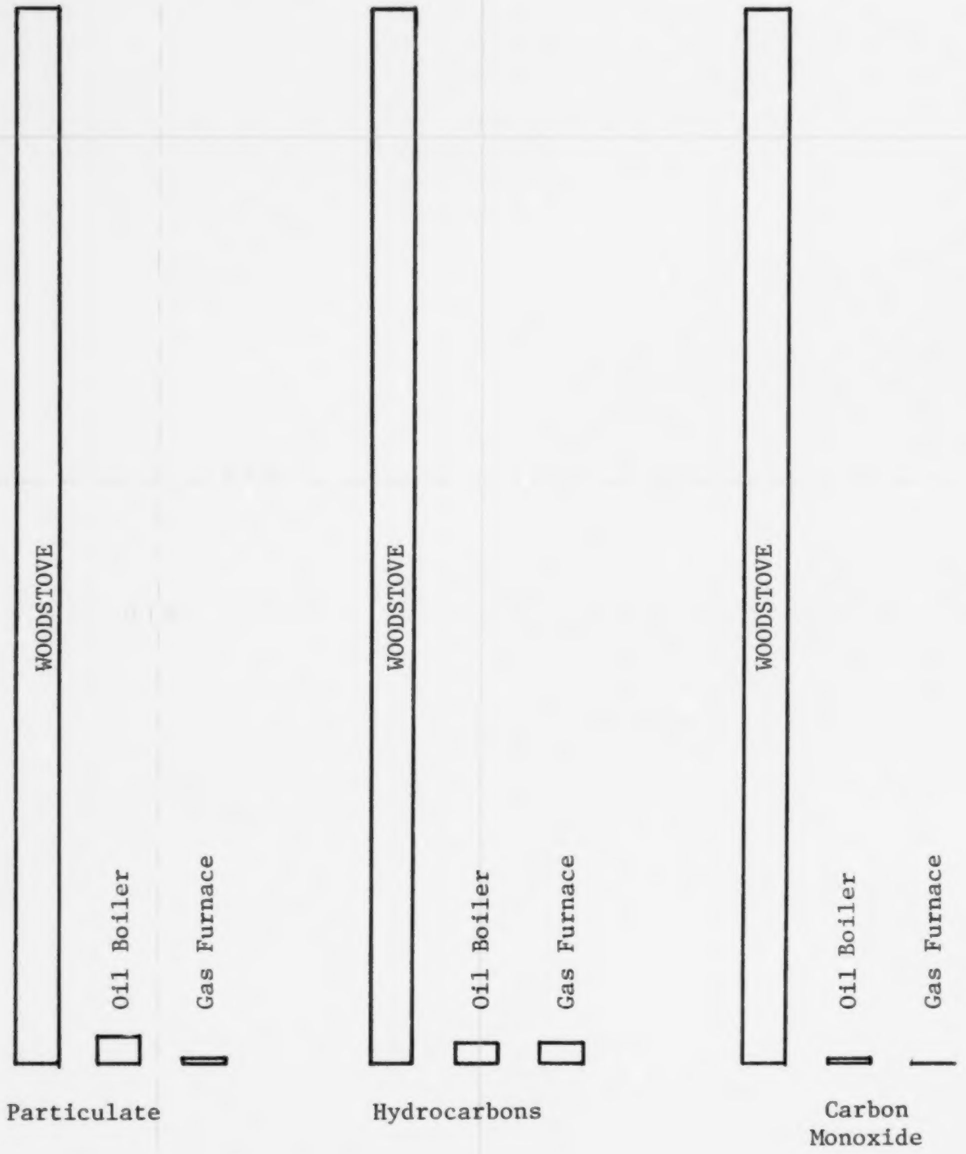


Figure 1. EMISSIONS FROM RESIDENTIAL HEATERS PER UNIT OF HEAT DELIVERED TO THE DWELLING. Efficiencies of 50% (woodstove) and 75% (gas furnace and oil boiler) were assumed. Emission factors were taken from reference 3, and values were normalized with respect to woodstove emissions.

EPA Form 2350-4 (8-80)
TYPING GUIDE SHEET

permit the throttling of inlet air to the point where the products of combustion are fuel-rich enough to give such problems. However, the use of stack-mounted dampers may thwart the designer's intentions.

This paper describes work which is currently under way at the VPI Solid Fuels Research Laboratory. It was originally our intention to generate and make available a great deal of information concerning catalysis of woodstove effluent. For example, which metals or combinations of metals are effective, how much precious metal loading is required to achieve a given amount of oxidation, what the ignition (or "light off") temperatures are for different catalyst choices, what conditions (stoichiometries, inlet temperatures) are suitable for operation without formation of secondaries, advantages of pellets or beads* vs. monoliths, etc. Funding limitations have prevented achievement of all these goals.

Current activities are directed toward the following:

1. Determination of the chemical and physical changes which occur to woodstove effluent during passage over noble metal catalysts.

2. Determination of the magnitude of pressure drop required for a stove to operate with a pellet-bed catalyst.

The first goal is important because of concern over what design safeguards are necessary to prevent formation of the secondary species already discussed. The second goal is related to economics and the desire to develop a retrofit type of unit. Pellet or bead-beds provide, by virtue of the tortuous paths they create, superior oxidaion levels per unit mass of precious metal, and are therefore, inherently less expensive. However, they also tend to have high pressure drops, and any stove utilizing such a catalyst will almost certainly require induced draft. This sounds like a serious drawback, but several things should be considered. The catalyst can produce large increases in gas temperature, and the potential increase in stove efficiency is wasted if the additional thermal energy is not transferred to the living area. A stack-mounted heat exchanger is thus a natural feature of a catalyst-equipped stove, and the same motor could be used to drive both the draft-inducing and room air circulating fans. To allow for occasional power failures, the system would also need provision for a bypass to open automatically upon draft loss. The amount of power required appears to be very low.

EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus and procedures used for these tests are an outgrowth of earlier work by Jaasma and Metcalfe (3). The transient nature of hand-fired combustors dictates that measurements be taken at brief time intervals, else important variations in the dependent variables may be unnoticed. Figure 2

---

* The term "pellet" refers to small, barrel-shaped structures, and "beads" refers to spheres.

TYPING GUIDE SHEET

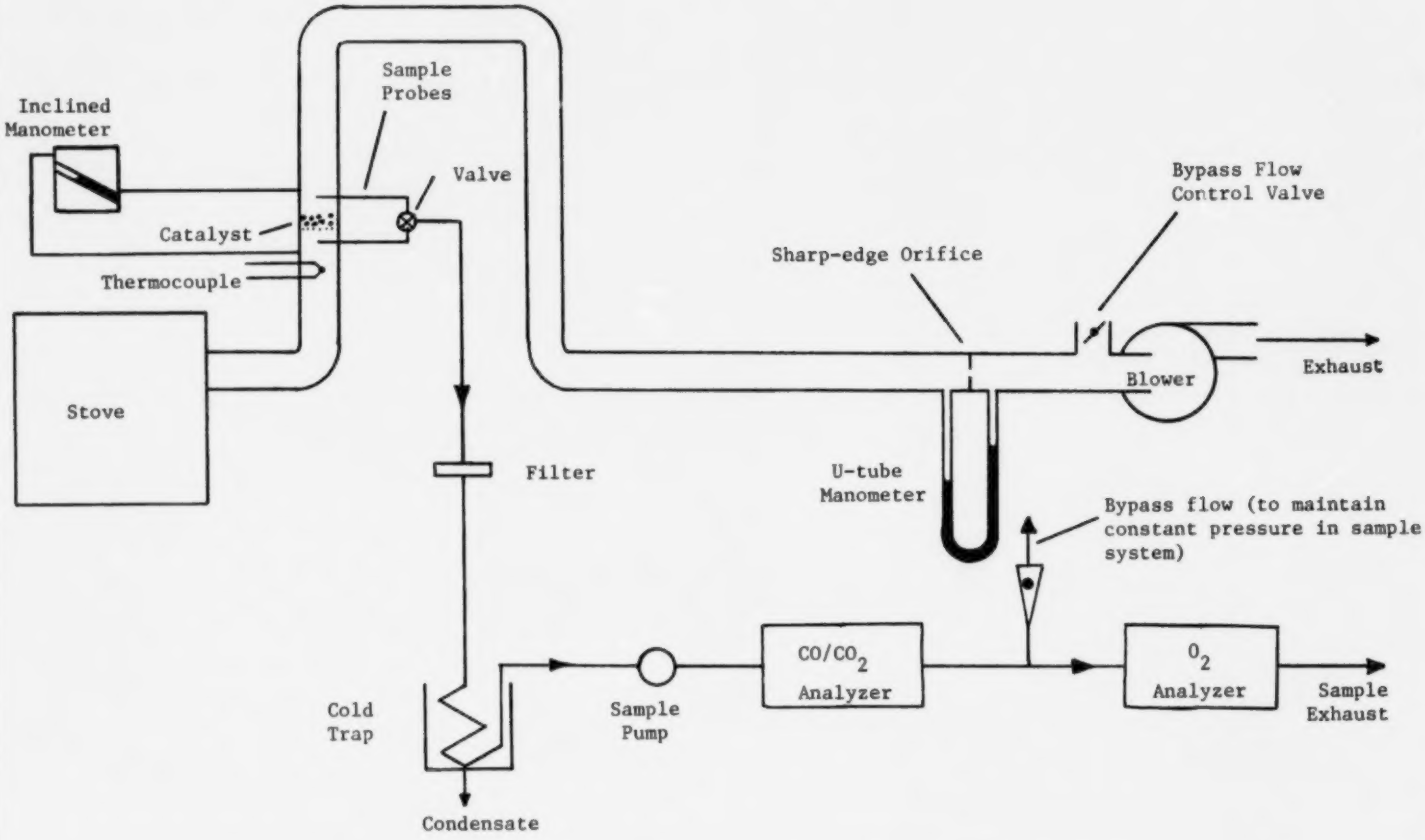

Inclined Manometer
Sample Probes
Valve
Catalyst
Thermocouple
Stove
Filter
Cold Trap
Condensate
Sample Pump
CO/CO$_2$ Analyzer
U-tube Manometer
Sharp-edge Orifice
Bypass Flow Control Valve
Blower
Exhaust
Bypass flow (to maintain constant pressure in sample system)
O$_2$ Analyzer
Sample Exhaust

Figure 2. Schematic Representation of Catalyst Test Facility

water prior to the gases' entering the analyzers. A combination CO/CO_2 analyzer and a zirconia-sensor oxygen analyzer were used to obtain the (real-time) CO, CO_2, and O_2 concentrations of the sample gases (dry basis). The concentrations were recorded at periodic intervals. Filter loading was inferred by rotameter measurement of the bypass flow, and the filter was renewed whenever the sample flow could no longer be maintained at the normal level.

The purpose of this work was to study the effect of the catalyst on the effluent chemical composition, rather than to assess the problems which might result during start-up of an initially cold catalyst. Thus, a smokeless fuel (charcoal) was used to preheat the stove and catalyst. Once the catalyst was hot, the test fuel (hickory stickwood which had been stored indoors for ca. 9 months, or freshly cut oak) was loaded onto the bed of coals and the stove door was closed. Data were recorded manually at random intervals during each burn.

RESULTS

The data of Table 1 are a sampling of the results which have been observed thus far. Each group of data is part of a single run, and the entries are given in the order which the data were recorded. An oxygen analyzer was not available at the time the first set of data was taken. The conversion efficiency listed in the table is defined as

$$\begin{array}{l}\text{CONVERSION}\\ \text{EFFICIENCY}\end{array} \equiv \frac{\%CO_{\text{pre-catalyst}} - \%CO_{\text{post-catalyst}}}{\%CO_{\text{pre-catalyst}}} \times 100$$

All gas concentrations are measured and reported on a dry basis, and the presentation of only a conversion efficiency for CO was dictated by the lack of an unburned hydrocarbon analyzer. The oxygen concentrations may lack accuracy because of CO and unburned hydrocarbons in the sample gas*, but the data are probably good to ± 1% O_2. Most of the data taken thus far are for high-fire (stove damper open, bypass flow adjusted to give high firing rate) operation, with the stove half full of wood following fuel addition. None of the conditions studied have given measured oxygen concentrations of less than 1% in the flue gas. Detector tubes were used to check for the presence of amines above or below the catalyst during the first fun shown in the table, and none were indicated.

The fourth data group is actually a continuation of the third group. The first data point for the green (cut two months earlier) oak represents conditions five minutes after addition of 7.6 kg of oak to the remains of the hickory fire. The increasing CO_2 concentrations and stack temperatures are indications that the combustion rate was increasing during the 45 minute interval represented by the four data points.

---

* The oxygen analyzer used in this work has interference effects due to the presence of combustibles in the sample gas.

TYPING GUIDE SHEET

is a schematic of the test apparatus which has been set up to allow real-time measurements of stack gas flow rates and chemical composition. For these tests, where chemical change is the primary variable under study, the catalyst is located in the flue. For a commercial version the appropriate location is inside the stove, due to the desire to maintain the catalyst at temperatures where significant catalytic activity will occur.

WOODSTOVE

The woodstove used in this investigation has primary and secondary air inlets, the primary air entering through a thermostatically controlled damper mounted on the door. The damper is pre-set by the manufacturer so that primary air flow will not be completely stopped, regardless of thermostat setting. The secondary air inlet consists of two 1.3 cm diameter holes located in the top half of the door. The holes can be partially or fully closed off by means of a manually adjustable plate. The stove has a false bottom with a grate in the center. Air which enters through the damper passes to the center of the stove and comes up through the grate, past the fuel. The secondary air inlets are intended to bleed air into the region above the charge, thereby providing oxygen for combustion of volatiles before they escape. The secondary air inlet was closed during all the tests reported here.

STACK CONFIGURATION AND INSTRUMENTATION

The stove was used with the stack configuration and instrumentation shown in Figure 2. The stack diameter is 15 cm, and a 3.56 cm sharp-edge orifice is located downstream of the catalyst test section. A bypass flow is adjusted to give the desired flow rate (pressure drop) through the orifice. The orifice gives an easily measured pressure differential (ca. 1 in. H_2O) which, when combined with the measured gas temperature at the orifice, gives the molar flow rate of stack gas at any location between the stove collar and the bypass tee. This flow, when combined with concentration measurements of CO, CO_2, and O_2, determines the mass flow rates of these species. The stack could be insulated ahead of the orifice to help avoid condensation of organic species in the stack and on the orifice plate, although this was not done for this work. Other tests with non-catalyst equipped stoves have shown that the orifice does not clog rapidly enough to create appreciable inaccuracy during a run.

An inclined manometer was used to measure the pressure drop across the catalyst bed. The pellets rested on top of a stainless steel screen, and for some runs a second screen was placed on top of the pellets to prevent them from moving during the higher stack gas flow rates. The pellets used were 1 by 2 millimetres, and were obtained from a catalytic convertor ordinarily used for oxidation of CO and unburned hydrocarbons in the exhaust stream of a Chevrolet Camaro.

Sample gases were continuously withdrawn from either above or below the catalyst, depending on the setting of the three way valve. The depth of the pellet bed was approximately 1.5 cm. The gases were drawn through a filter and an ice trap to remove particulate, condensable organics, and

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

TABLE 1. PERFORMANCE OF A 1.5 cm CATALYST BED IN A 15 cm FLUE

FUEL	APPROACH STREAM CONDITIONS $\%O_2$	$\%CO$	$\%CO_2$	^oC	^oF	CONVERSION EFFICIENCY, %	PRESSURE DROP ACROSS CATALYST, in. H_2O	FIRING MODE
Dry Hickory	---	0.16	11.2	430	806	90	1.1	High Fire
"	---	0.30	8.5	400	752	90	1.1	"
"	---	0.42	6.6	360	680	95	1.1	"
"	---	0.06	0.8	90	194	0	0.9	End of Burn
Dry Hickory	7.	0.36	12.5	340	644	58	1.0	High Fire
"	3.5	0.71	17.0	470	878	80	0.9	"
"	4.5	0.50	15.8	470	878	68	0.9	"
"	7.5	0.07	12.3	440	824	86	0.8	"
Dry Hickory	5.5	1.07	13.5	360	680	90	0.8	High Fire
"	1.0	1.35	18.8	510	950	93	1.4	"
"	3.0	0.90	16.3	520	968	97	1.3	"
"	6.0	1.0	13.0	400	752	98	0.6	Damped
Green Oak	11.	0.90	7.6	320	608	89	1.2	High Fire
"	10.	1.1	8.3	330	626	92	1.2	"
"	10.	1.3	9.0	380	716	92	1.3	"
"	9.	0.50	11.8	420	788	96	1.2	"

Conversion efficiencies ranged from 58 to 98%, not counting the 0% (end-of-burn) value at the finish of the first run. Noble metal catalysts are not effective at temperatures below around 200°C (400°F), and it is expected that at the end of a burn the catalyst will become inactive. Eleven out of the fifteen data points having inlet temperature of 320°C or above showed excellent conversion efficiencies of 89% or better. Decreases in CO concentration across the bed were usually accompanied by CO_2 concentration increases which were greater, presumably due to hydrocarbon or particulate oxidation. Better data could be obtained by use of two analyzer trains (one sampling above the catalyst and one sampling below), since there is a 10 second response time when the current system switches from one probe to the other. The additional expense of a second train seems unnecessary, since the trend is already very clear.

Pressure drop across the catalyst bed ranged from 0.6 to 1.4 inches of water, depending mainly on the flow rate through the stack. There was no evidence of clogging during the burn-out period of the runs. Start-up clogging was not studied due to the preheating technique used. For the most part, the draft system gave adequate flow so that smoke did not enter the room when the stove door was opened. Opening the door during high-fire conditions sometimes allowed smoke into the room, indicating that the draft was not adequate for all operating conditions encountered.

DISCUSSION

Time and funding have precluded the accumulation of enough data to fully characterize the chemical changes and pressure drops associated with various conditions of the effluent as it approaches the catalyst. The data reported herein are highly preliminary, but indicate that significant conversion can be achieved under conditions of 1.5 cm pellet-bed depth with pressure drops on the order of 1 in. of water. The pressure drop would be decreased if the same volume of pellets was spread out over a larger area, as would be the case for an in-the-stove convertor. Spreading out the pellets has a second advantage, the reduction of the tendency of pellets to lift due to the gas flow through the bed. The Table 1 results were obtained for automotive catalyst pellets having a metal loading around 0.05%. This amount of metal loading is very low compared to loadings which the author considers to be economically viable for use with woodstoves. The light-off temperature is reduced by increasing the metal loading, and both the conversion efficiency and catalyst life are extended by use of heavier loadings. We are in the process of acquiring beads with loadings many times the automotive pellets' loading. In quantities greater than 500 kilograms, the cost of beads with five times the loading of the pellets used in these tests would be around $12 per stove, assuming the same volume of beads was required. It is likely that less beads would be required due to the higher metal loading. Additional costs would naturally be involved due to the need for bead support and a fail-safe, induced-draft system. The power requirement for an induced-draft system which would provide a stack flow equal to twice the flow during these experiments would be on the order of 0.2 kW (0.15 horsepower). This flow would likely be adequate to prevent smoke from entering the room under any operating condition. The preliminary results reported here indicate that a pellet or bead-bed system has potential for use in stoves. Further study is required to answer questions regarding the potential problem areas of secondary product formation, catalyst life, and start-up. Future experiments addressing these topics are planned, as well as chemical equilibrium calculations for the carbon-hydrogen-oxygen-nitrogen mixtures which can result from wood combustion. It is recognized that equilibrium will not necessarily be achieved due to kinetic limitations, but it is felt that the calculations will provide some insight into the species which could be formed under various operating conditions.

ACKNOWLEDGEMENTS

This work has been partially supported by grants from Sierra Manufacturing and Shenandoah Manufacturing. The author is very greatful for their assistance, and in particular for their willingness to support work which will be of eventual use to the entire solid-fuels industry and the public.

REFERENCES

1. DeAngelis, D. G., D. S. Ruffin, and R. B. Reznik, "Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment," U.S. Environmental Protection Agency report No. EPA-600/7-80-040, March 1980.

2. Urban, C. M., and R. J. Garbe, "Regulated and Unregulated Exhaust Emissions from Malfunctioning Automobiles," Society of Automotive Engineers, paper no. 790696, June 1979.

3. Jaasma, D. R., and C. I. Metcalfe, "Real-Time Measurements of Emissions from an Airtight Woodstove," paper No. CSS/CI-80-20, presented at the Spring Meeting of the Central States Section of the Combustion Institute, March 1980.

A SIMPLIFIED TECHNIQUE FOR MEASURING CONDENSABLE PARTICULATE EMISSIONS FROM WOODSTOVES

by: Stockton G. Barnett and Damian Shea
Department of Earth Sciences and Department of Chemistry
State University of New York
Plattsburgh, N.Y. 12901

ABSTRACT

The recent surge in woodstove usage in the United States has begun to cause air pollution problems, especially in certain urban areas. This is of particular concern because carcinogenic chemicals have been identified in woodstove smoke. Additionally, respiratory problems can develop from smoke particles lodged in the lungs. It is therefore important that the types of woodstoves and the way they are burned be studied to determine their effects on air quality. In order to do these studies an effective method of measuring condensable particulates in flue gas emissions is necessary.

The authors have developed an effective technique to measure condensable particulates in flue gases from woodstoves. A low cost, high volume sampler was designed for this technique which concentrates flue gas particulates on filter paper. An important feature of the sampler allows room air to bleed into the sampler tube to cool flue gases and thereby insure complete condensation of the flue gases into droplet form.

During test runs conducted in the project, the flow rates of both stack and sampler were monitored. After months of testing, a thermopile-type flowmeter manufactured by Teledyne Hastings Raydist (PCI-30) was discovered which reliably measures stack velocities without being affected by either high temperature or by liquid droplets in the flue gases.

To determine emission factors, the filter residue of each sample was weighed, and when related to the wood's burning rate, the condensable particulates per kilogram of wood burned was determined.

Tests were run for condensable particulates in the following generic types of stoves: thin-walled convective heater, single door box stove, double door step stove, single door step stove, box stove with inclined baffle , step stove with horizontal baffle, cast crossdraft stove, plate crossdraft stove, ceramic crossdraft stove, cast crossdraft stove modified into a true downdraft stove, and an experimental stove. Results are not yet available, but they will be presented at the International Residential Solid Fuel Conference in June 1981.

INTRODUCTION

The recent dramatic increase in woodstove usage in the United States has begun to cause concern about woodstove air pollution, particularly in certain urban areas. Studies have begun to analyze this problem in Waterbury, Vermont, in parts of Oregon, and other areas as well. There is particular concern because carcinogenic chemicals have been identified in airtight woodstove smoke. Additionally, respiratory problems may develop from smoke particles lodged in the lungs.

In this project we developed a simplified method of determining condensable particulate emission factors for woodstoves. We also attempted to identify types of stoves and particular stove burning patterns which produce both the least and greatest amount of condensable particulate emissions in residential wood burning situations. One test stove (a thin-walled convective box heater) was subjected to minor structural alterations to determine if its particulate pollution could be easily reduced. A prototype stove was also built and tested for particulate emission levels. The results of this part of the study will be reported in the International Residential Solid Fuel Conference in Oregon, scheduled for June 1981.

Further studies need to be done relating these particulate pollution results to the abundance of carcinogens in various stoves under a variety of burn conditions.

PROCEDURES

GENERAL

The condensable particulate flue gas sample runs reported on herein varied from 3 to 8 hours in duration with 5 hours being the most common. This generally allowed for 2 to 3 cycles of charging and wood burning. The exceptions to this are the sample runs made at 200°F stove temperatures where only one burning cycle took place.

The analyses utilized split red oak and sugar maple in approximately 4 to 6 inch by 18 inch pieces with a moisture content of 30% to 40% (oven dry basis). Analyses with dryer and wetter wood were also run to determine the effect of varying moisture content on particulate emissions.

In this project scales were not used to weigh the stove and its wood content but, instead, wood was weighed before it was put into the stove (stove had been brought up to temperature), and the sampling was either continued to the point where only coals remained in the stove or wood was removed from the stove and weighed after the test was conducted. In this manner the rate of wood burning in kilograms per hour could be determined. Although this technique was probably adequate in light of the magnitude of differences in test results between the different stoves, it is potentially the largest source of error in the testing procedure. It is possible that an error of plus or minus one pound could develop (± 15% on slow burn (200°F) tests and ± 10% on all other tests).

The results of all tests are expressed as grams of particulates per kilogram of wood. Since the wood weight includes its moisture, the results of our tests should be increased by about 30-50% if one desires comparisons for oven dry wood.

Most tests were run at an average external stove temperature of 300°F, a temperature determined by observations in about 15 local homes to be the most common burn temperature in northernmost New York. Four stoves were subjected to more extensive testing. These tests were made at various stove temperatures to determine the relationship between stove temperature and particulate emissions and to determine if internal changes in the stove could reduce particulate pollution.

Since the temperature at which the stove is burning has a marked effect on the rate of particulate emissions, the use of a new thermostatic device developed by Barnett was employed wherever possible. This new thermostat enabled us to determine more precisely the relationship between particulate emissions and burn temperature because the temperature of the stove could be maintained to within ± 20°F of the desired temperature.

Each time a flue gas sample was taken, the following parameters were measured: stove temperature, internal stack temperature (about 1.5 feet above the stove), sampler air velocity, and stack air velocity. In about half of the sample runs stack gases were sampled about 1.5 feet above the stove. In the other runs inaccessibility to the stove pipe made it necessary to sample at the top of the stack. Measurements of creosote accumulation in the stack of one relatively extensive creosote forming stove over a month period indicate that 10% or less of the flue gas condensable particulates accumulate in the stack.

SAMPLING OF STACK GASES

The technique which we used is similar to the one utilized by the E.P.A. Method V test whereby stack gases are sampled with a suction device and the particulates are collected on filter paper. Our technique was a modification of that method in that a higher volume sampler was used (from 250 - 1100 cu. f.p.m.). Sampling was conducted for short intervals of 60 seconds spaced 10 minutes apart instead of for long continuous time periods of one hour or so as in Method V. In this modified technique an estimate of the total amount of condensable particulates generated by the stove can be determined. Also the dynamic manner in which the individual stove produces particulates during the entire burn can be determined. This approach is useful in stove development as well as evaluation. For an example of these features see Figure 1. (It can be seen that the sampling was frequent enough and changes in particulate emissions slow enough that the area under the curve (total particulate emissions) can be adequately determined.)

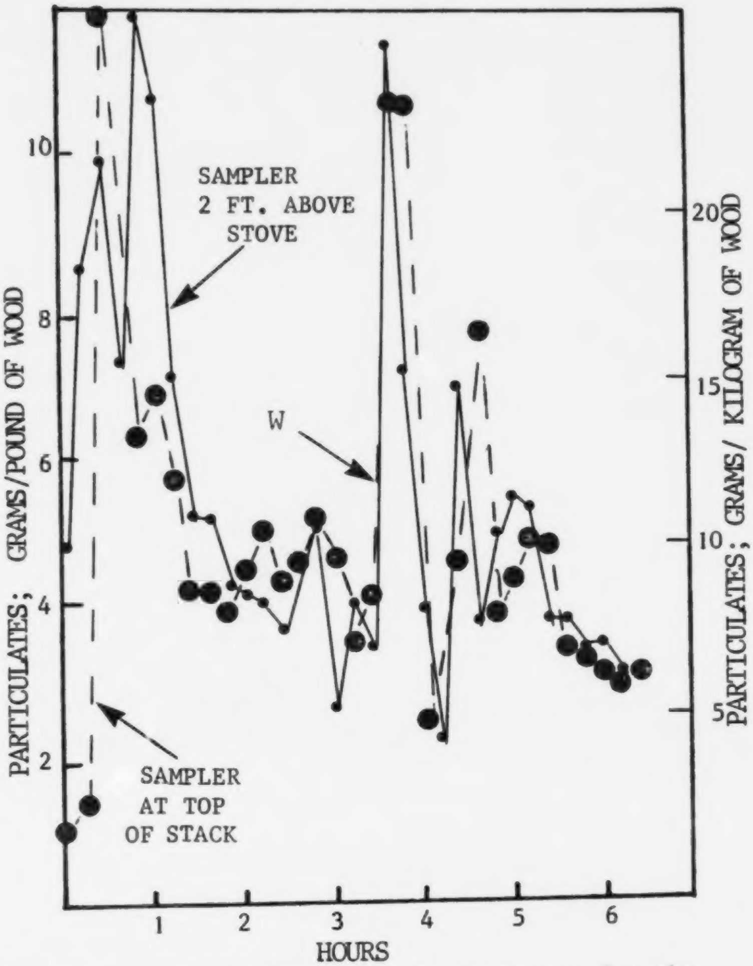


Figure 1. Particulate emission patterns for the thin-walled convective heater at 300°F stove temperature with wood moisture 20% (oven dry basis). Sampling was alternated from a sample position at the top of the stack to a position two feet above the stove top.

The Sampler

The high volume sampler we used was constructed by simply adapting a standard canister vacuum cleaner (bag removed) to a fabricated barrel-shaped filter paper holder with a 2.1 inch opening. We used 2.5 inch Schleicher and Schuell No. 589 (rapid) filter paper. After a sample was taken, the filter paper was air dried for 24 hours and then weighed on a Mettler balance to determine the weight of particulates which had accumulated. Three pieces of clean filter paper were kept near the Mettler balance and weighed at the time filter papers for the project were weighed in order to compensate for changing weights of filter paper caused by changing humidity.

Condensation of Flue Gases on the Filter Paper

It is imperative that a sampling technique simulate the real world situation whereby flue gases enter the cool atmosphere, condense and are available to be inhaled into human lungs. Therefore the sampling procedures must condense flue gases before they reach the filter paper. This problem was solved in a cumbersome way by Shapiro, et. al, 1980. They noted that over half of the condensable particulate matter passed through their Method V filter paper and condensed on the impinger plates along the sampling train. We have attempted to simplify the sampling procedure so that flue gases can be condensed before they reach the filter paper, thus avoiding the necessity of using a long sampling train.

First the authors determined the flue gas temperature at which flue gases completely condensed. This was accomplished by making a 5 hour sampling run on the thin-walled convective heater in which the stack temperature at the point of sampling (2.5 feet above the stove) was 250-270°F. During this same burn the flue gases were sampled at the top of the stack where the stack temperature was 120-150°F. Samples were first taken at the lower location then at the upper location at 5 minute intervals. The results (shown in Figure 1) indicate that no additional condensation takes place between 250-275°F and 120-150°F. In fact, about 10% is lost to stack accumulation in the form of creosote. This means creosote has completed its condensation by 250-275°F and therefore a standard sampling tube can be used at stack temperatures of 250° or lower.

A second, longer sampling tube was constructed which contained about fifteen ¼" holes along it. These holes allowed room air to bleed into the sampled gases in a turbulent fashion. This condition caused sample gases to be cooler by the time they reached the filter paper. Two five hour sample runs were made alternating the long perforated tube and the original short tube at 3 minute intervals at stack temperatures of about 250°F. Both of these sample runs retrieved essentially the same amount of particulate matter (see Figure 2), further supporting the results of the earlier upstack-downstack experiment which indicated that if the stack temperature at the point of sampling is less than 250-275°F condensation is complete.

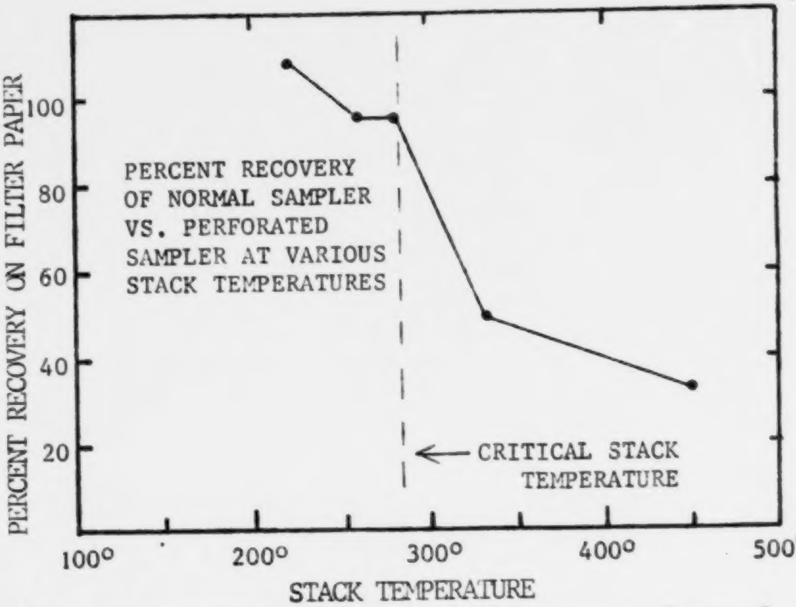


Figure 2. Percent recovery on filter paper of normal sampler vs. new perforated sampler. Note that at stack temperatures below about 275°F both samplers recover essentially the same quantity of particulates.

The same type of sampling, alternating the two samplers, was conducted for two additional sample runs when the stack temperatures were significantly higher. In one run they were 300-350°F and for the other run they were 400-450°F. The results, shown in Figure 2, indicate that retrieval on the simple short tube is incomplete and reduces to only about 30% at a 400-450°F stack temperature. Complete condensation occurs in the long tube because the temperatures are well below 250°F at the filter paper. In fact, they never exceed 90°F.

A final test at high stack temperatures was run using only the long perforated sampler and alternating its position from a low hot portion of the stack to a high cooler portion of the stack. The results were almost identical (within 10% of one another) indicating that at high stack temperatures the long perforated tube is highly effective.

In conclusion, flue gases condense at about 250-275°F and a simple sampling tube is effective in capturing condensed particles as long as stack temperatures at the sampling location are at least that low. At higher stack temperatures the longer perforated sampler is highly effective.

AIRFLOW MEASUREMENTS

It is important to determine what percentage of the flue gases is being sampled so that an estimate of the total particulates passing up the stack can be determined. This requires measurement of air velocities in both sample and flue pipe. The air velocity entering the sampler was measured before the sample was taken and after the sample was taken using a Kurz 440 air flow meter. An average of these two readings was used to provide and average value for the sampler's intake air flow. (Tests indicated that this velocity declined linearily with time so only a before and after velocity is necessary.) Attempts were made to measure the air flow velocity in the flue pipe using first the Kurz 440 air flow meter and then the thermopile-type Teledyne Hastings Raydist (PCI-30) air flow meter placed high in the stack where temperatures were always below 170°F.

After approximately eight months of experience with both air flow meters several conclusions can be drawn. The Kurz meter is subject to all-too-frequent failure and is not acceptable for stack measurement, although for measurements at room temperature it is quite reliable. The Hastings meter was generally reliable.

A wind tunnel was constructed to determine the accuracy of the Hastings meter at elevated temperatures (up to 170°F). The results indicate that the meter was not affected by differences in temperature. The flue pipe of a burning stove was then blocked. The stove door was opened and the wind tunnel was placed at the stove door entrance to determine if the passage of condensed flue gas droplets across the meter's sensor affected the readings. No change in the meter's reading was observed. Water vapor was then sprayed from an atomizer into the wind tunnel to see if the meter could be affected at all by liquid droplets. Moderate to high spraying rates markedly affected the meter but a low spraying rate did not. It can be concluded from these experiments that the Hastings meter provides reliable readings up to 170°F (sensor must be placed high in stack) and that droplet concentration in woodstove smoke is not high enough to distort readings. The meter thus reliably measures flue gas velocities under the testing conditions reported herein. However, if woodstoves are burned at rates exceeding stove surface temperatures of about 400°F, stack temperatures will be too high for this meter (it can only withstand 200°F). The inability of the meter to function at stove temperatures above 400°F is generally not a hinderance to analysis of residential woodburning since our observations of the burning habits of about 15 local stove owners in northernmost New York (one of the coldest parts of the country) indicate that stove temperatures over a burning season exceed 400°F only a small percentage of the time.

It was found that by placing the Hastings probe in a 4 to 6 foot length of 4 inch fluepipe at the top of the stack, velocities were increased sufficiently such that measurement error was greatly reduced. The probe needed to be checked for creosote buildup every half hour and cleaned with oven cleaner, as required. Also both the Hastings and Kurz airflow meters required calibration checks before each sample run.

The earliest stove tests in this project were conducted using the Kurz meter to measure flue gas velocity. The more recent discovery of both this meter's unreliability and the high level of performance of the Hastings meter prompted us to conduct almost the entire research project a second time using the latter meter. The results of the first series was reported on by Barnett & Shea (1980). Their results are markedly similar to those currently being obtained. Because of the vagaries in the Kurz flowmeter data we must request, however, that their results not be quoted.

Calculation of Condensable Particulates Emission Factors

The weight of particulates (in grams per kg of wood) was calculated for each sample by the following equation:

$$\text{particulates (grams per kilogram of wood)} = \text{weight of particulates on filter paper} \times \frac{\text{stack flow (C.F.M.)}}{\text{sampler flow (C.F.M.)}} \times \frac{\text{60 (no. of minutes per hour)}}{\text{wood burning rate (kilograms per hour)}}$$

RELIABILITY

Two sample runs were conducted to determine how much particulate matter was passing through the filter paper. The sample runs were conducted during dirty vs. relatively clean flue gas conditions to determine if a differential filter paper collection situation exists. In both runs 6 samples were taken in rapid succession for a total time of 12 minutes. For the first two samples No. 589 BH filter paper was used in order to test for repeatability in readings with that paper. The next sample was on Wattman No. 1. The next two samples were on two pieces of Wattman No. 1 back-to-back to assume a complete recovery situation. The final sample was on No. 589BH to determine if the particulate emissions had changed in the 12 minutes. In both the clean and dirty stack sample runs the first two No. 589BH filters agreed within 10% of one another. About 60% of the double Wattman's was recovered on the No. 589BH paper for the clean burn, a burn producing particulates at about 2 grams/kg of wood. About 70% of the double Wattman's was recovered on the No. 589BH paper for the dirty burn, a burn producing particulates about 19 grams/kg of wood. Therefore, to compare results for this report with those of EPA Method V, our results should be multiplied by about 1.5.

To evaluate the reproducibility of our technique, ten five-hour sample runs, herein called standard runs, were made on a thin-walled convective heater at a 300°F burn as well as additional runs at 200°F and 400°F. Figure 3 illustrates the temperature dependence of emission factors as well as the variation in analyses in the 10 standard runs. A statistical analysis was conducted on the deviations of the ten standard runs from the best fit line. The 95% confidence limit (two standard deviations) is 15%. This represents the probable error of this technique, an error which includes all the variables involved in the procedure. This level of error is much smaller than the measured differences in emission factors of many of the stoves, allowing the differences in particulate emissions between stoves to be determined.

RESULTS

In this project the authors developed an effective technique to measure the condensable particulates in the flue gas emission of woodstoves. The major problems of measuring stack gas velocity and assuring that flue gases

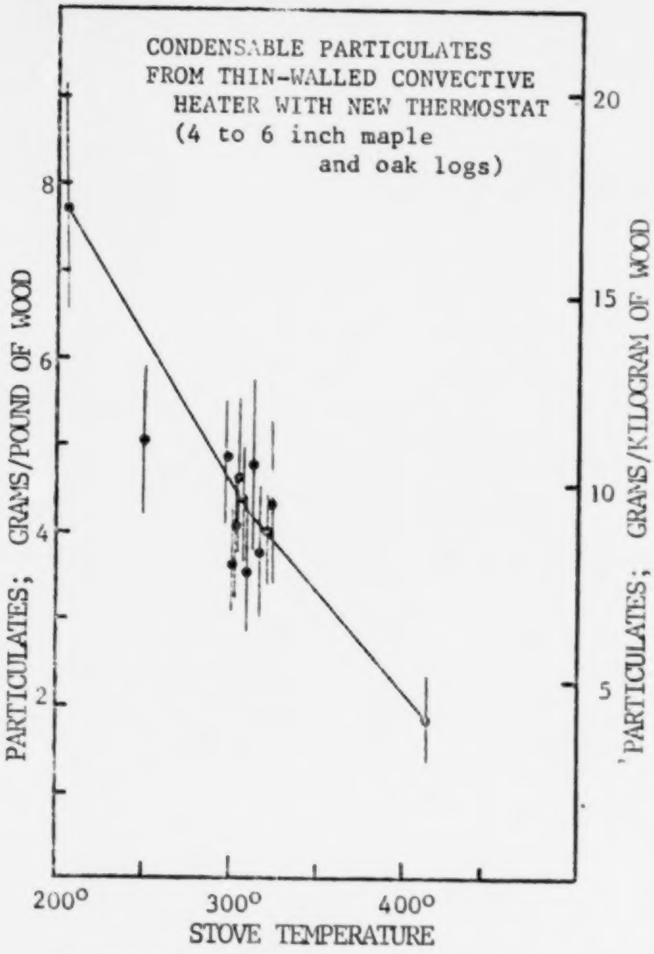


Figure 3. Condensable particulates from thin-walled convective heater equipped with new thermostat. Note variation in the 10 "standard runs" made at about 300°F stove temperature and the temperature dependence of emission factors.

have been condensed in the sampler and captured on the filter paper have been resolved using the authors' technique. Tests were done to determine the reliability of the technique using a variety of burn conditions and stove types typical to residential wood stove heating. It was found that the technique is reliable to within ±15% and therefore comparison of particulate emissions produced by various woodstoves and under various burn conditions can be made.

REFERENCES

Barnett, S.G. and Shea, D., 1980, Effects of Woodburning Stove Design on Particulate Pollution: Program and Abstract of the Seventh Annual Lake Champlain Basin Environmental Conference.

DeAngelis, D.G., Ruffin, D.S., and Reznik, R.B., 1980, Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment EPA - 600/7-80-040, 145 pgs.

ABSTRACT

CONTROL OF EMISSIONS FROM RESIDENTIAL WOOD BURNING BY COMBUSTION MODIFICATION

by

John M. Allen
Battelle - Columbus Laboratories

Air pollution emissions from residential woodburning appliances are affected by many variables, including stove design, operator techniques, and fuel properties. Several of these variables have been investigated in the laboratory to identify relationships between the independent combustion variables and the stove emissions.

The two most significant emissions are carbon monoxide and organic species, the latter including both hydrocarbons and some partially oxidized materials. These organic materials are also the source of creosote when they condense in the flue and are collected on the cooler surfaces before being emitted to the atmosphere. They also include some polycyclic aromatic hydrocarbons which have been found to be carcinogenic. The two principal mechanisms of pollution formation are incomplete combustion in the active burning region usually associated with a restricted air supply, and wood pyrolysis without burning of the pyrolysis products. Several factors can prevent or restrict the burning of these combustible species, including low temperatures, limited oxygen supply, poor mixing, and lack of an ignition source.

Several approaches are identified to reduce the emissions from residential wood stoves, including mode of burning provided by the stove design, operator techniques in using the stove, and characteristics of the fuel being burned. Some problems in applying some of the corrective actions are noted, and promising techniques are recommended for development.

CONTROL OF EMISSIONS FROM RESIDENTIAL WOOD BURNING BY COMBUSTION MODIFICATION

INTRODUCTION

Increased usage of wood as a residential heating fuel has resulted from the rising prices of other fuels and public skepticism as to reliability of normal fuel supplies. This increase has occurred with the widespread impression that wood burning is environmentally clean. Increased wood use is being encouraged by DOE, equipment manufacturers, and many environmentalists, all with a very limited technology pertaining to emission factors, and even less technical basis for reducing emissions. In many instances the residential stove manufacturers and operators are adopting stove designs and operating practices conducive to increased emission factors. This accentuates the environmental significance of the increased quantity of wood burned residentially.

BURNING CHARACTERISTICS OF WOOD

Residential cord wood is generally characterized as either a hardwood or softwood specie, either green or air dried, and normally consists of both split and round pieces. These characteristics all have small but significant effects on emissions. The chemical composition and heating value vary remarkably little between species when measured on a dry basis, the soft woods being only slightly more calorific due to their slightly higher resin content. The most significant burning characteristic affecting emissions is the phased burning phenomena. The three phases, drying, pyrolysis, and char burning take place successively for any one particle of wood, but all three phases occur simultaneously during much of the burning in a stove. As heat is added to a piece of wood, drying of the surface layer occurs first. This is followed by thermal pyrolysis of this same layer simultaneous with drying of the underlying wood. The pyrolyzed gas may or may not burn at the surface. The effluent steam from the drying absorbs both latent and sensible heat. It also tends to block convective heat flow from the surroundings into the wood. This heat flow blockage retards the wood pyrolysis, and thus slows the overall rate of wood burning.

As the burning continues and the surface layer becomes converted to a char, pyrolysis gas from the wood below the char layer must diffuse through the charred surface before it can react with atmospheric air to burn in a flame. This subsurface pyrolysis is exothermic, however, and once started can consume a significant portion of the wood without requiring oxidation at the surface or oxygen penetration into the wood. Moisture from the core of the wood can, in some cases, transpire outward through a hot char layer resulting in CO formation by the water-gas reaction. The rate of pyrolytic gas evolution often exceeds the availability of oxygen at the surface.

resulting in unreacted or partially reacted species leaving the wood even when flames surround each piece of wood. This primary burning within a pile of wood thus results in incomplete burning, with primary combustion products containing CO and organic pyrolysis products. Subsequent oxidation with a secondary or supplementary air supply is required to complete the burning. The limited pressure drop normally available in the air supply is often not sufficient to provide the penetration and mixing required for effective secondary combustion. This results in ultimate emissions of CO, hydrocarbons, and other organic species including polycyclic aromatic hydrocarbons (PAH).

Some of these materials condense onto the chimney walls as creosote, some condense into submicron particulates within the stove and chimney passages, and some leave the chimney as a gas. The fraction that is retained on the filter as particulates by the standardized EPA Method 5 sampling procedures depends on several factors. These particulates are typically only a third or less of the total unburned hydrocarbons leaving the stove some of the remainder, which is not deposited in the stack as creosote, presumably condenses onto and into additional atmospheric particulates after leaving the chimney.

The rates of these phenomena relative to the local supply of air can become critical in the formation of organic emissions from the stove.

TYPES OF STOVES

There are at least four generic types of naturally drafted wood burning stoves as shown in Figure 1. The designs are categorized as to the direction of air flow through the burning wood and wood inventory within the stove. Each of these types is shown in the figure adapted to provide secondary air supply, and thus permit secondary burning. Although considered very desirable, effective secondary burning has seldom been attained in the laboratory, and apparently is rarely attained in residential applications. The updraft design appears to be most conducive to organic emissions because the inventory of wood within the stove is extensively heated by primary combustion products depleted of oxygen. The true down-draft burning mode can be very clean burning, when up-flow countercurrents within the bed are prevented. This type of burning delays the rapid release of pyrolysis products until active and complete burning can be achieved.

EXPERIMENTAL PROGRAM AT BATTELLE

The stove test facility at Battelle utilizes independent, prefabricated, insulated chimneys for each stove, exhausting within a high bay area in the building. Thus, the chimney effects on draft are not affected either by outside wind or by the building's transient pressure fluctuations. Radiant stoves are mounted on electronic scales, such that total weight losses associated with fuel burning can be continuously monitored. Normal combustion products (CO_2, NO_x and CO) are continuously monitored, together with O_2 to determine combustion parameters including excess air and total

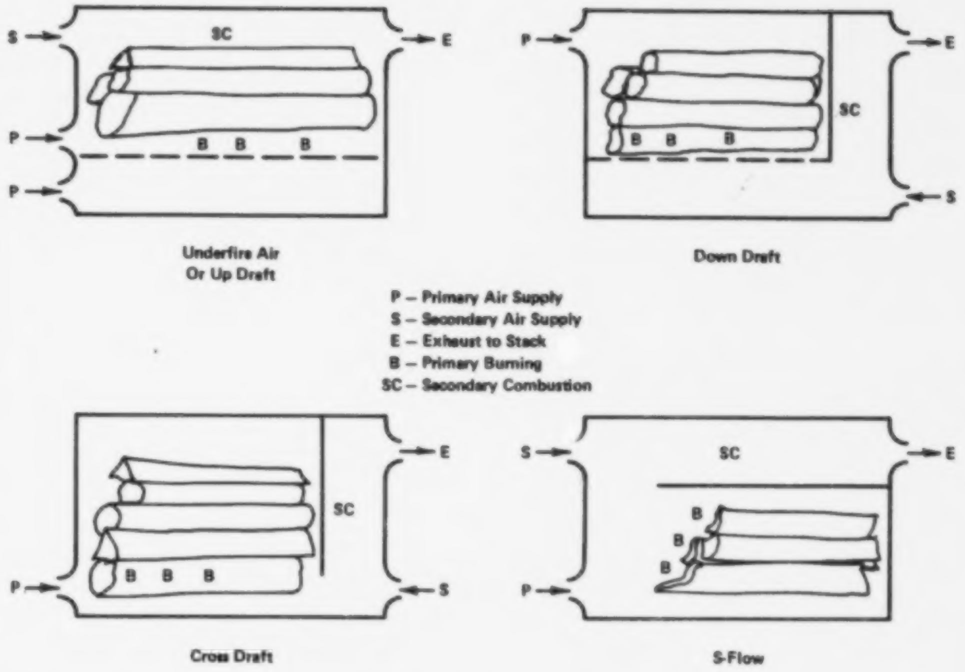

S
SC
E
P
B B B
P
Underfire Air Or Up Draft
P
SC
E
B B B
S
Down Draft
P – Primary Air Supply
S – Secondary Air Supply
E – Exhaust to Stack
B – Primary Burning
SC – Secondary Combustion
E
SC
B B B
P
S
Cross Draft
S
SC
E
B
B
B
P
S-Flow

FIGURE 1. GENERIC DESIGNS OF WOOD STOVES BASED ON FLOW RATES

air flow. Total hydrocarbons (THC) are monitored with a FID instrument providing continuous readings. This measurement is interpreted as a semiquantitative measurement of all organic emissions, whether they ultimately leave as vapor or particulates.

Particulate and gaseous samples are collected simultaneously during some tests for PAH measurements. This is done high on the stack, using an EPA Method 5 filter, followed by a water cooled XAD-2 column. This packed column collects by adsorption the hydrocarbons such that they can be later measured and analyzed in some detail.

Our usual test procedure is to operate the stove as a batch process, with a test run immediately following a pre-run, burning the same fuel at the same burning rate. The stove operating procedures generally follow those specified by the recently proposed ASHRAE standard procedures. We have not normally used the standardized wood brands as specified by that standard, because we have found that the brands result in high emissions of unburned fuel which are not representative of customary residential operation of wood stoves. We use either conventional split air-dried cord wood, or slightly smaller air-dried, 4 by 4 lumber. These 4-inch pieces of lumber have provided an accurately reproducible shape, including a diagonal cut to provide triangular pieces. The weight loss (fuel burned) and emissions are recorded each minute until the weight loss equals 95 percent of the weight of test fuel fired. The monitored flue gas compositions are machine averaged for each entire run. Emission factors are then calculated using the averaged gas composition and the weight of wood burned. Effects of a decreasing rate of weight loss (i.e., decreasing burning rate), and the changing composition of the fuel being burned during a run are not accommodated by this calculation technique. Those factors might slightly increase the emission factors, over those calculated by the time averaging technique.

Figure 2 shows the time variation of hydrocarbon emissions during a typical run burning the triangular 4 x 4 oak fuel. The total hydrocarbon emissions rose to above 10,000 ppm (measured as methane) during the early burning, and reduced to less than 1000 ppm when the wood pyrolysis had converted most of the remaining fuel into char. Simultaneously, the O_2 in the flue gas dropped below 5 percent during most of the wood pyrolysis, and increased to about 13 percent during the char burning. This increase in O_2, occurring late in many runs, is assumed to come from an increasing fraction of the primary air flow by-passing the active primary burning area.

In Figure 3 the carbon dioxide and carbon monoxide measurements of the flue gas are shown for the same run. It must be recognized that these flue gas analyses cannot be related exclusively to the direct primary combustion effluents, even though no secondary combustion was identified in this run. The secondary air admissions dilute and cool the primary combustion products by an unknown amount.

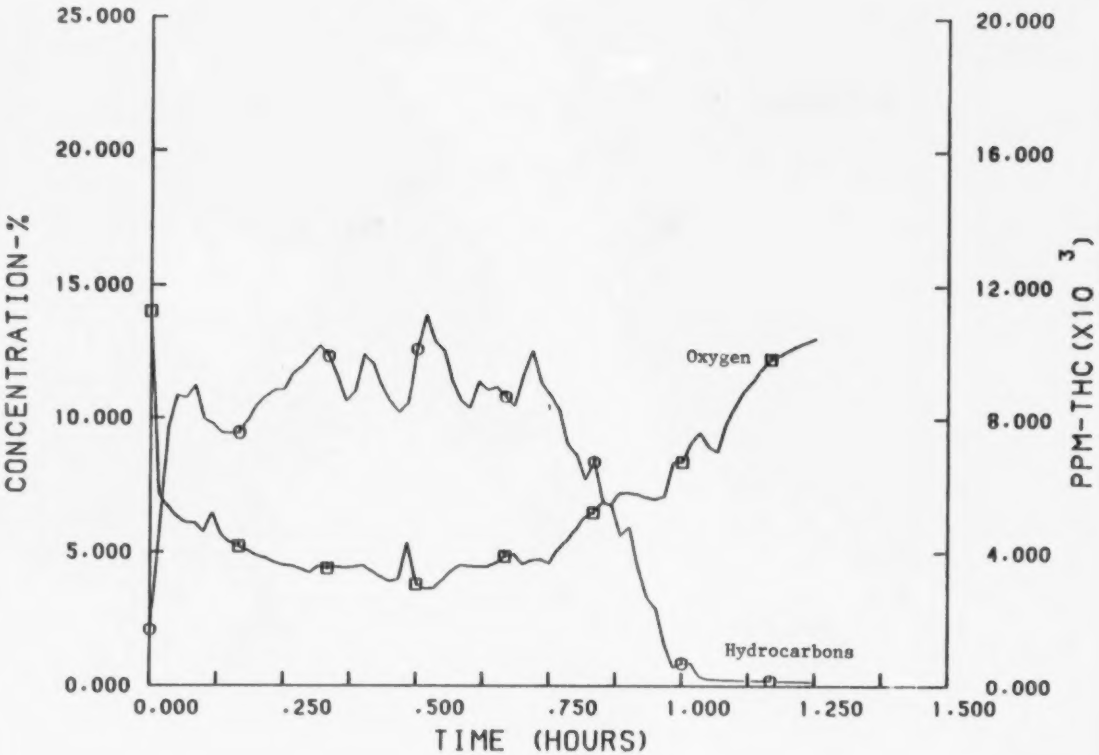


FIGURE 2. HYDROCARBON EMISSIONS DURING A RUN BURNING CURED OAK

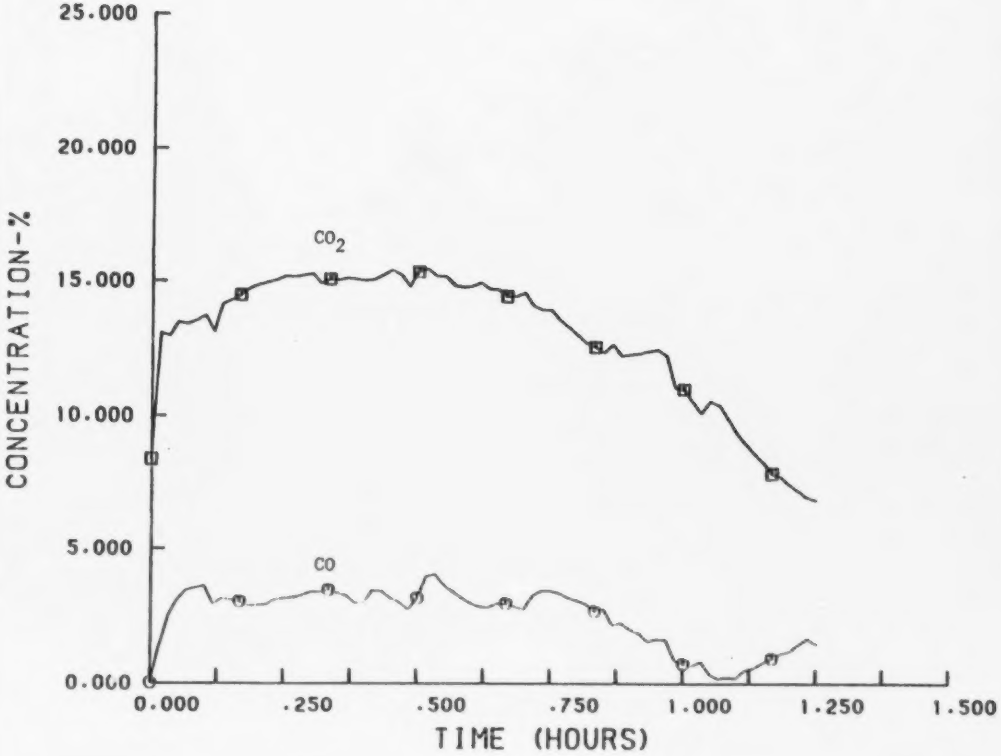


FIGURE 3. CARBON MONOXIDE EMISSIONS DURING A RUN BURNING CURED OAK

It is interesting to compare the HC emissions with CO emissions They tend to increase together, as both are related to starved air operation. Figure 4 shows these emissions averaged over complete burning cycles in several stoves operated at different rates of burning. At low burning rates (i.e., stove outlet temperatures below 400 F) the hydrocarbons are approximately equal to CO emissions (HC/CO=1), whereas at high burning rates (i.e., stove outlet temperatures above about 600 F) the hydrocarbons are only about 1/5 the CO emissions (HC/CO=0.2). When these stove emissions get very high, the CO emissions increase relative to the hydrocarbons more than proportionally as these correlations would indicate.

VARIABLES AFFECTING EMISSIONS

Discussed below are a few of the variables that affect emissions, with experimental data showing these effects.

BURNING RATE

Figure 5 shows the effects of burning rate on THC emission factors when burning oak 4 x 4's in four different stoves. These emission factors were determined from time averaging of emissions measured over a complete burning cycle related to the weight of wood burned. It is evident that the emission factors obtained at high burning rates are not representative of stoves operated at the reduced burning rates often used in residential heating.

The combustion in the stoves is air-controlled once the wood is adequately ignited. At reduced rates of air flow into the combustion chamber, caused by partially closing the inlet air damper, a reduced burning rate of fuel is obtained. The reduced wood burning rate is frequently accompanied by increased oxygen content in the flue gas, indicating a larger fraction of the total air flow bypasses the active combustion region. Thus, the restricted air-flow burning is accompanied simultaneously by higher CO and THC emission factors, and higher overall excess air ratios.

MODE OF BURNING

Three of the four generic designs of air flow path were incorporated into one stove (Defiant) for a direct comparison of emissions. The up-draft mode with the hearth was achieved by opening the damper thus permitting the primary combustion products and pyrolysis products to pass directly upward and out of the stove. In the side draft mode all primary combustion products passed under the side arch or baffle, and through the more extensive internal passages before leaving the stove. In both of these modes the fire rested on an impervious hearth. The Defiant was also modified to burn in the down draft mode. In the down draft mode the fire bed was entirely supported on a grate with the bed area reduced by about one third from the other designs, and all the products passed downward through the grate, under the arch, and then through the same passages as used in the side flow design. In this mode the primary air was supplied through an opening in the end door, rather than through tuyeres at the hearth level.

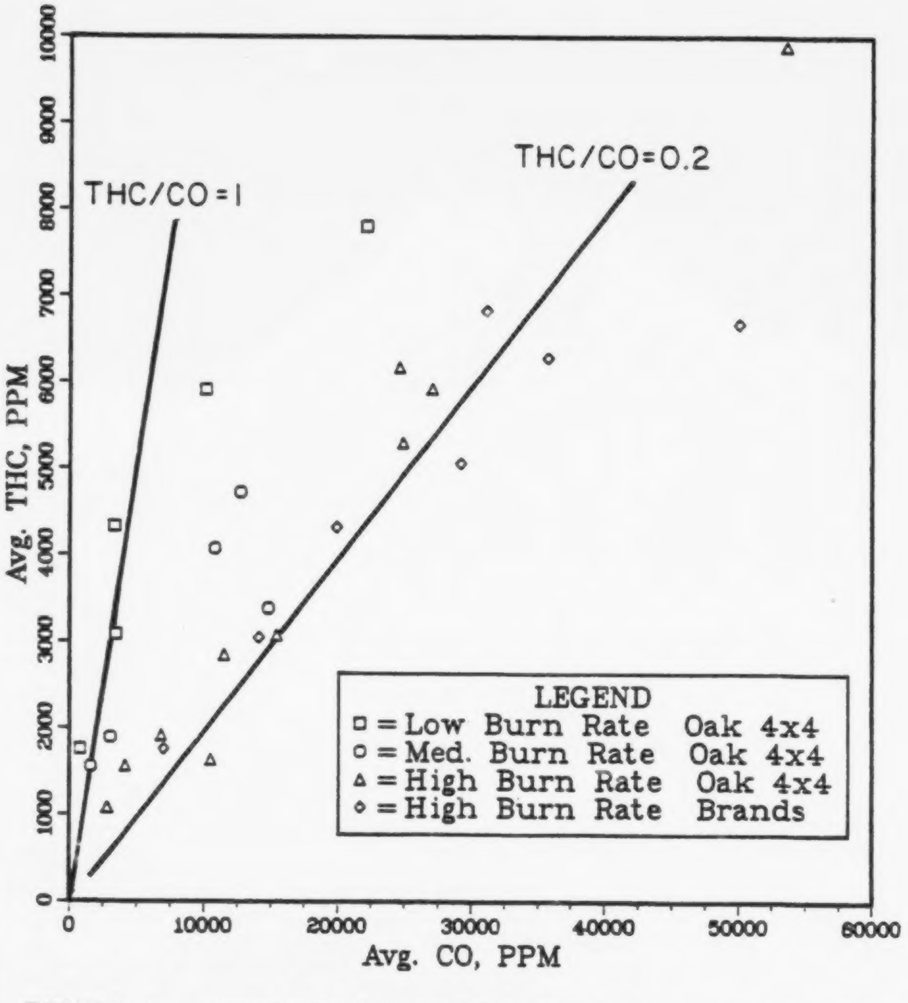


FIGURE 4. CORRELATION OF THC AND CO EMISSIONS FOR SEVERAL STOVES

FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD, BEGIN SECTIONS HERE

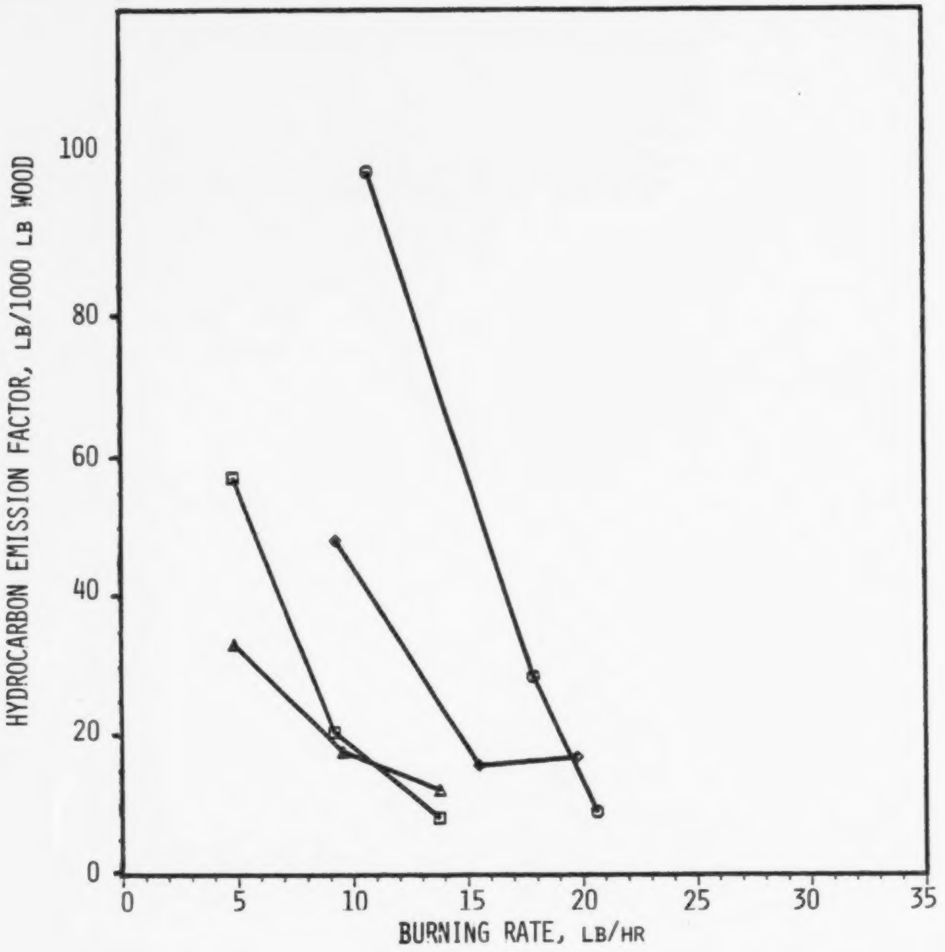


FIGURE 5. THC EMISSION FACTORS FOR SEVERAL STOVES

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The results of the tests are summarized in Table 1. As can be seen from the data, there is no large difference between the three modes of operation of one stove. Both emissions and emission factors are shown for the three different modes of burning for various burning rates. The downdraft mode at high burning rates is consistently low in THC emission factors. When the burning rate is low the thermal buoyancy forces result in a local updraft flow (countercurrent) within parts of the bed, overcoming the overall average down flow through the bed. This results in channeling and flow recirculation within the bed, and rapid pyrolysis of wood throughout the bed. Extensive pyrolysis products can thus be released into the counter stream and ultimately pass with the channeled down flow out of the bed without burning.

Another stove (Riteway) was modified to burn in the updraft mode with all the primary air traveling upwards through a grate supporting the burning wood. All the combustion products then passed out through the top of the combustion chamber. This mode of burning resulted in higher THC and CO emission factors than the other modes at comparable burning rates, although the PAH emissions do not support this trend.

The Dumont high turbulence burner produced lower emission factors than normal radiant stoves in either the updraft or side draft modes when burning oak fuel. The emission factors were then comparable to the lowest values obtained with good down draft burning.

COMBUSTION AIR PREHEAT

While operating a stove in the down draft mode, two pairs of runs were conducted to identify possible effects of preheating of the primary air on emissision factors for combustibles. The time averaged emissions for the entire runs were converted to emission factors as shown in Table 2. Oak logs were burned in these runs. Even with the low emission factors down draft burning, reductions were obtained when the primary air was preheated with an outside source. It is not certain if this same effect would be observed with other modes of combustion. In the downdraft mode of burning the heated incoming primary air should have the greatest effect, by promoting early pyrolysis of wood thus adversely affecting emissions of combustibles. However, these pyrolysis products cannot easily bypass the active burning area at the downstream edge of the bed as in other modes of combustion. Reductions in emission factors were observed as shown in Table 2.

Preheating secondary air is assumed to have no effect on emissions unless secondary combustion is established or can be initiated by the preheat. When burning wood which emits large quantities of combustibles early in a burning cycle (dry fir brands) secondary combustion was initiated when a 5 scfm stream of 442 F secondary air was admitted. This constituted about 15 percent of the total air supply.

TABLE 1. EMISSIONS FROM DIFFERENT MODES OF BURNING FUEL: Oak 4 x 4's

Emissions		Emissions Factors lb/1000 lb wood				
THC, ppm	CO, percent	PAH	THC	CO	Excess Air, percent	Burning Rate, lb/hr
		Side Draft Mode (Defiant)				
8300	1.8	ND	112	420	340	6.3
1900	0.6	ND	12	63	110	11.8
2800	1.2	ND	15	100	60	17.4
6200	2.5	0.035	28	190	40	18.7
1800	0.5	0.045	9	40	130	18.4**
		Down Draft Mode (Defiant)				
3100	0.2	ND	56	67	560	7.3*
3100	0.2	ND	56	64	560	10.3*
600	0.4	0.050	5	59	180	13.7
1000	0.5	ND	7	61	120	18.4
		Up Draft Mode with Hearth (Defiant)				
1800	0.1	ND	113	90	2050	6.3
1600	0.2	ND	19	33	290	10.2
1100	0.3	ND	8	37	140	14.4
		Up Draft Mode with Grate (Riteway)				
6700	2.5	ND	34	220	80	14.4*
7100	3.6	0.018	32	280	40	16.5
5900	2.7	ND	34	170	80	20.9
9900	5.4	ND	42	400	30	27.1
6400	2.3	ND	33	200	80	31.8*
		High Turbulence (Dumont)				
200	0.1	0.011	5	25	920	24.1*
300	0.3	ND	2	30	110	21.9*

* Oak Logs
** Green Pine

TABLE 2. EFFECTS OF PREHEATED PRIMARY AIR ON EMISSIONS
Data averages for each of 4
complete tests

Down Draft Burning of Oak Logs

	Ambient Primary Air (80 F)		Heated Primary Air (370 F)	
Burning Rate lb/hr	15.6	11.3	15.1	16.0
Emissions				
CO, percent	0.3	0.3	0.2	0.2
THC, ppm	1000	900	300	200
Emission Factor, lb/1000 lb wood				
CO	44	48	20	15
THC	10	11	2	1

SECONDARY COMBUSTION

During the test program there were very few occurrences of distinct secondary combustion when not being deliberately promoted. Even when secondary combustion was attempted, if and when it was obtained, it occurred only at high burning rates and for only a short period of time (usually less than five minutes).

The stove used for these observations has a separate secondary combustion zone. For the observation and determination of secondary combustion a pyrex window and a thermocouple were placed in the secondary combustion chamber. Different woods were burned so that different burning rates and emissions could be tested for secondary combustion.

During one test the secondary air flow was intermittently stopped. With the secondary air inlet closed, emissions were high. The inlet was then suddenly opened. One-minute data extracts from this test are shown in Table 3. When the secondary air inlet was opened an audible noise was heard, and the initiation of secondary combustion was indicated by the thermocouple located in the secondary combustion chamber. The initial pulse of secondary air was presumably heated above the equilibrium inlet temperature, as the supply duct was surrounded by the hot gas. Along with the indicated temperature increase of about 100 C (170 F), there was a decrease in emission levels. Later during that test when secondary combustion was still apparent, the secondary air inlet was suddenly closed. The results were a decrease in temperature in the secondary combustion zone and a sharp increase in emissions. Secondary combustion was not reobtained upon reopening of the air inlet after several additional minutes.

The concept of secondary combustion is very effective for the reduction of emissions. However, it is very difficult to attain when a stove is operated at lower burning rates more typical of consumer operation, where both the temperature and the turbulence level are lower.

AMOUNT OF WOOD CHARGED

The amount of wood placed into the stove at one loading will have a large influence in the amount of pyrolysis products leaving the stove. The emissions go up with the increase in wood inventory at the same burning rate due to the increased quantity of wood exposed to the heat and thereby subject to preburning pyrolysis.

To demonstrate the effect of increased wood inventory in a stove two tests were run. In one test, 12.9 pounds were burned and the other test burned 41.9 pounds of wood. The wood was the same for both tests (oak 4 x 4's) and the stove was operated at the same air setting during the same day. The tests were run using the side draft mode of burning discussed earlier in the text.

TABLE 3. EFFECTS OF SECONDARY COMBUSTION ON EMISSIONS
Burning Fir Brands at Approximately 30 lb per hr

	Prior to Secondary Burning	After Secondary Burning Initiation	During Secondary Burning	After Secondary Air Flow Stopped
Time, hr. min	15:10	15:13	15:59	16:01
Flue Gas Composition				
O_2 percent	3.6	4.6	7.6	5.37
CO_2 "	15.1	14.6	13.0	14.3
CO "	2.3	0.1	0.1	1.51
THC ppm	8200	680	430	4100
Temperature in C 2nd Comb Zone, F	613 (1135)	712 (1314)	656 (1212)	617 (1143)

Table 4 shows the comparison of the two tests, demonstrating that as the wood inventory is increased the emissions increase. The burning rates for the two tests were essentially the same but the large charge resulted in approximately doubling the emission factors.

Stoves that keep the wood from pyrolyzing by isolating the wood inventory from the heat during combustion should reduce emissions. The only course open to the operator to reduce emissions from this mechanism is to add small quantities of wood more frequently.

WOOD SIZE AND SHAPE

The size of wood has a large effect on the rate of pyrolysis. The smaller pieces of wood result in: a shorter distance for the pyrolysis products to diffuse, a larger surface area to mass ratio, and a reduction in the time required to heat the entire piece of wood. The heat transfer coefficient is generally twice as high for with-the-grain transfer as opposed to across the grain transfer. Therefore split wood will heat up and pyrolyze quicker than unsplit wood of the same size under the same conditions.

The effects of size and configuration were investigated in tests burning cured oak in the down draft mode. The stove was run at the same conditions for each test, so the burning rates were different, dependent only on the wood. The smallest wood used was oak kindling which was four to six inches long and had an equivalent diameter of about one inch. It was all split, there were no round sticks used. The other three configurations of wood had the same length (11 to 14 inches) with an equivalent diameter as is indicated. The differences were: the split wood was triangular and was split from large round pieces of oak without bark, the 4 x 4 wood was triangular and was sawed from 4 x 4's cut diagonally, the rounds were round oak logs, the bark was left on. All tests burned about the same amount of wood (14 to 16 lbs).

Figure 6 shows the emission data. As expected the split kindling resulted in the highest emissions, the larger round pieces had lowest emissions.

MOISTURE CONTENT OF WOOD

The moisture in wood depends on the specie burned, and the degree of drying (curing) before burning. The water present in the wood increases the amount of heat required to raise the wood to its combustion temperature thus reducing the rate of pyrolysis of the wood and reducing excessive organic emissions that are released early during the burning of kiln dried wood. We observed this in our tests, but the observations of J. Shelton are more definitive. Figure 7 shows his data, plotted under the realistic assumption that combustion inefficiency is equivalent to unburned fuel being emitted.

TABLE 4. EFFECTS OF AMOUNT OF WOOD CHARGED ON EMISSIONS

Side Draft Burning of Oak 4 x 4's
Data averages for each of 2 complete tests

Mass of Charge, lb	12.9	41.9
Burning Rate, lb/hr	17.4	19.2
Excess Air, %	62.9	58.1
Stack Temperature, F	680	660
(C)	(360)	(350)
Emissions:		
CO, percent	1.2	2.5
THC, ppm	2800	5300
Emission Factors, lb/1000 lb wood		
CO	100	220
THC	15	26

TYPING GUIDE SHEET

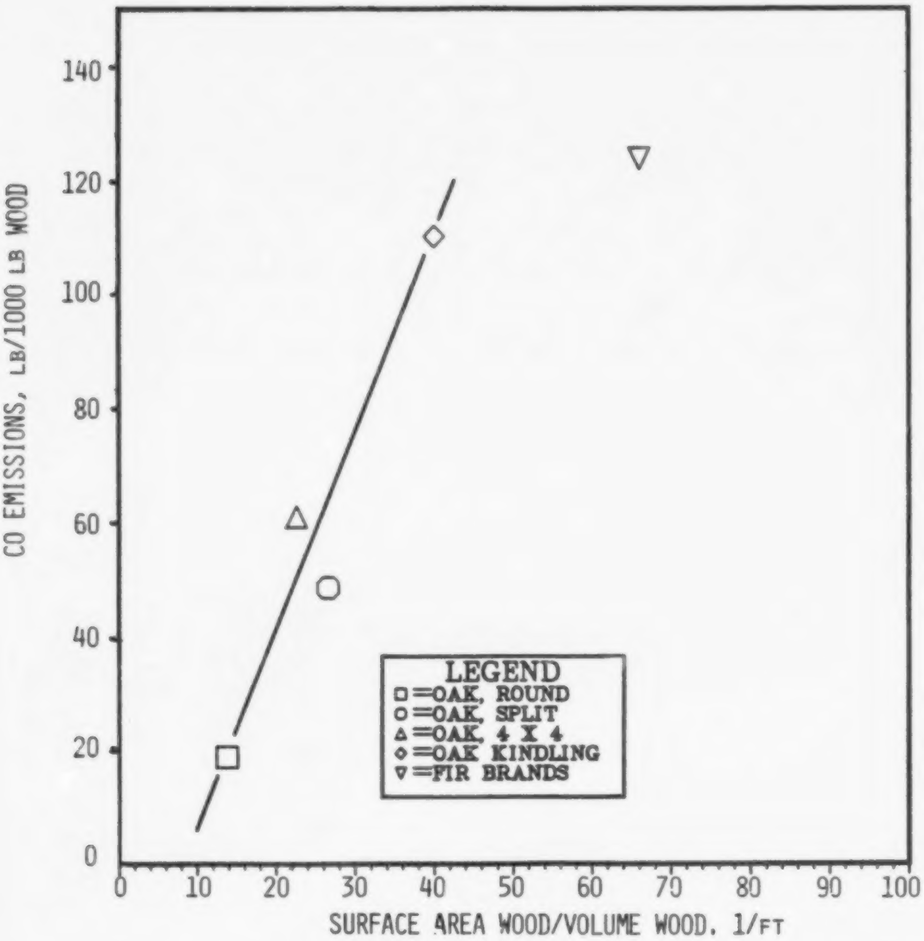


FIGURE 6. EFFECT OF WOOD SIZE ON CO EMISSION FACTORS

EPA-287 (Cin.)
(4-76)

TYPING GUIDE SHEET
FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

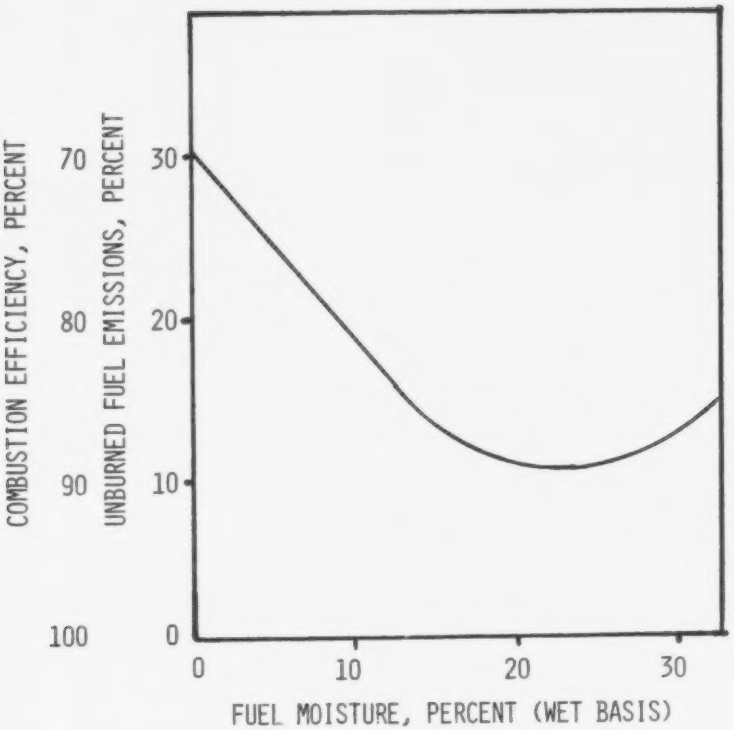


FIGURE 7. EFFECTS OF MOISTURE IN WOOD ON UNBURNED FUEL EMISSIONS

DATA FROM SHELTON ET AL ASHRAE TRANSACTIONS
VOL. 48 PART 1 1178

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA: OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
1/3"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

COMMERCIAL HIGH TURBULENCE BURNER

A residential wood burning appliance has been developed under a DOE contract by Professor Hill at the University of Maine. The burner demonstrates that increased efficiencies can be obtained with an improved design of the combustion and heat recovery system. The burner is a residential boiler (water heater) for a central heating system that incorporates several factors beneficial in controlling air pollution emissions. The combustion is supported by both forced draft of combustion air and induced draft of flue gases, such that a high turbulence level can be maintained in the burning areas, yet not develop a firebox pressure exceeding ambient. It operates only at a fixed, relatively high burning rate (∿150,000 Btu/hr) comparable to one of the large radiant heaters. Several characteristics of this design favor low organic and CO emissions.

- High turbulence level in primary burning area
- Primary combustion products isolated from inventory of wood
- Inventory of wood cooled by water-jacketed chamber
- Burning confined to small portion of the wood inventory
- Refractory lined primary combustion area
- Refractory lined secondary combustion area
- Large pieces of wood utilized to reduce excessive pyrolysis early during burning cycle
- Burning restricted to high rates, with heat storage provisions to accommodate lower heating requirements.

We obtained a commercial version of this unit and operated it burning stick wood as prescribed by the manufacturer. When the burner was fired with four very large split logs, one jammed in the hopper and remained partially unburned. When fired with the recommended size of split logs, operation was reliable with low emissions. When fired with smaller sizes of split logs the emissions increased only slightly. Table 5 shows the measured emissions when the burner was run until the blower was automatically turned off. When operating properly the emissions are appreciably lower than the representative radiant heaters. Even when burning brands to deliberately maximize early hydrocarbon emissions or when faulty fuel performance was encountered, the THC emission factor was not as high as in the more conventional radiant stoves. When properly burning the more appropriate split oak logs the CO emission factors are also much lower than from the radiant heaters.

These data demonstrate how appreciable reductions in emissions can be obtained with the application of several combustion modification techniques. Unfortunately many of these techniques are not applicable to the naturally drafted radiant stoves.

TABLE 5. EMISSIONS FROM HIGH TURBULENCE BURNER

	High Turbulence Burner				Comparable Radiant Heaters	
Fuel Burned	Large Split Oak Logs	Split Oak Logs	Smaller Oak Logs(3" to 4")	Dry Fir Brands	Updraft W Grate Dry Oak 4 x 4	Side Draft Dry Oak 4 x 4
Burning Rate, lb/hr	22.1*	24.1	21.9	20.9	16.5	18.7
Excess Air, %	220	920	110	120	40	42
Emissions						
CO, %	0.6	0.1	0.3	1.6	3.6	2.5
THC, ppm	2000	200	300	1900	7100	6200
Emission Factors, lb/1000 lb						
CO	97	25	30	222	280	190
THC	18	5	2	16	32	28
PAH	ND	0.011	ND	ND	0.018	0.035
Stack Inlet Temperature, F (C)	247 (119)	343 (173)	331 (166)	285 (141)	950 (510)	703 (393)

* This run terminated with 31% of fuel unburned. One log jammed in the hopper and did not fall into the burning region.

CONCLUSIONS:HOW TO REDUCE EMISSIONS

As the result of this study there appear to be several combustion modification techniques available to reduce the emissions from wood stoves, with varying degrees of probable effectiveness, and different levels of acceptability to residential stove builders and operators. These techniques are summarized in Table 6, noting whether a modified stove design is required, special operator techniques are required, or specific fuel characteristics are required. This compilation of conclusions serves as a guide to indicate the more promising combustion modifications which should be developed in more detail to justify extensive reduction to practice by stove users. Modification which are designed to limit the formation of emissions in the fuel magazine and combustion regions are presented first, followed by modifications designed to consume emissions which were previously formed, by the primary combustion zone, in the secondary combustion zone, or in an add-on auxiliary system. In each category the modifications are presented in decreasing order as to their expected likelihood of being effectively reduced to practice.

TABLE 6. SUMMARY OF EMISSION CONTROL TECHNIQUES

Factors Adversely Affecting Emissions	Approaches for Possible Improvements	Principal Modifications Required	Applicable to existing Stoves
Premature Pyrolysis in Wood Magazine Within Stove	1. Prevent heating of wood inventory	Design	No
	2. Feed wood in frequent small amounts	Operation	Yes
	3. Use large wood pieces, low surface to volume ratio	Fuel	Yes
	4. Burn moderate moisture content wood to retard pyrolysis	Fuel	Yes
	5. Burn devolatilized wood, charcoal	Fuel	Yes
Pyrolysis Rate in Primary Combustion Area Exceeds Local Air Supply Preventing Complete Combustion	1. Maintain high rate of primary air supply, with ensuing high burning rates	Operation	Yes
	2. Focus air supply into limited burning area to prevent widespread burning	Design	Retrofit
	3. Maintain high turbulence in active combustion region	Design	No
	4. Limit quantity of fuel in active burning area, i.e. approach fuel-controlled burning	Design	No
	5. Maintain high temperatures in active burning area	Design	Retrofit
	6. Avoid sharp and/or frequent reductions in air supply rate	Operation	Yes

TABLE 6. SUMMARY OF EMISSION CONTROL TECHNIQUES (continued)

Factors Adversely Affecting Emissions	Approaches for Possible Improvements	Principal Modifications Required	Applicable to existing Stoves
Control of Emissions in Primary Burning Area	1. Provide high level of turbulence in burning area to promote mixing	Design	No
	2. Maintain high temperatures in burning area	Design	Retrofit
	3. Provide long gas residence time at the high temperatures	Design	No
	4. Duct pyrolysis products from magazine into burning area	Design	No
	5. Provide down draft combustion, with bed area reduction to accommodate low burning rates	Design	No
Control of Emissions in Secondary Combustion Zone	1. Maintain high temperatures	Design	Retrofit
	2. Use heated secondary air	Design	No
	3. Increase combustible content of primary combustion products	Design	No
	4. Provide anxiliary combustion using an ignition source and/or supplementary fuel	Design (Operation)	No
Add-on Systems Affecting Emissions Reduction	1. Use catalytic afterburner	Design	Yes
	2. Use separately fueled afterburner	Design	Yes
	3. Add heat storage capacity to the system, permitting other modifications to be acceptable for consumer utilization.	Design	Yes

Session 4: ENVIRONMENTAL ASSESSMENT AND CONTROL - HIGHLIGHTS FROM EARLIER SESSIONS

Chairman: Robert E. Hall
U.S. Environmental Protection Agency
Research Triangle Park, NC

HIGHLIGHTS FROM SESSION 1
OVERVIEW OF WOOD COMBUSTION ENVIRONMENTAL ASSESSMENT

by: Henry Anderson
Program Manager of Space Heating Appliances
U.S. Department of Energy
Washington, DC

The next speaker is Henry Anderson, who is from the Department of Energy, who will give our next presentation. Mr. Anderson is Program Manager for the office of Buildings and Community Systems within the Department of Energy. He manages research, development, and demonstration programs for residential, commercial, wood or solid fuel combustion appliances plus gas and oil-fired heating equipment. After receiving degrees in mechanical engineering from the University of Florida and University of Maryland, he served as Chief Systems Engineer for several U.S. Navy installations. Hank. . . .

Thank you, Bob. Welcome, and thank you for the chance to speak again. This is a recap of Session 1 which was an overview of the residential wood program. The sales of wood burning equipment are beginning to approach the sales of gas and oil-fired heat pump equipment. In fact, a recent EIA estimate on the consumption of wood is about a half a quad to six-tenths of a quad. A quad is 10^{15} Btu. It is a cube of cordwood one-third of a mile on a side. In the commercial and industrial area, the use of wood is about one and a half quads, maybe a little more than that, for a total of two quads. It is interesting to note that sales of wood burning appliances began to escalate especially after the oil embargo of 1973. For space heating in oil, the U.S. consumes around two and a half quads and for gas its around four quads, so you can see wood is beginning to have a real impact on space heating; and as the price of fuels like oil and gas increase, wood will become even more a factor. The total of industrial and commercial use of wood plus residential is two quads. Nuclear is around the same order of magnitude--about three quads. The overall use of energy in the U.S. is around 80 quads. The nuclear people, of course, get a lot more R&D money than we do. With nuclear, you cannot spread the waste in your garden. I think that wood is really a very strong contender.

In the world, one-tenth of the energy is supplied by biomass, which, of course, includes wood. Brazil gets one-half of its energy from wood. Brazil is facing what happened in Europe around 300 or 400 years ago. They are depleting their wood supply. There are vast areas of the Amazon Valley which have been deforested and are now being eroded. When that occurred in Europe, what saved the forests of Europe were two things--one was the plague, which reduced the demand on the wood--and the other was coal. They discovered coal so they used that instead of wood.

Right now we are at a point where there is only one long-term supply of fuel, and that is biomass. Coal, of course, is a long-term fuel but it is not in indefinite supply. What is interesting is the return to wood as a fuel, and it is important that we manage our resource with wisdom.

A paper which was presented by EPA, Mr. Schwengels, was on a systems approach in the jurisdiction of TVA on biomass. The important thing to note is that this is a systems approach which started with the assessment of the fuel source on a regional basis. It also included the management of the forests and awareness of the other demands on the forests such as the timber industry, whatever other forest products industries are there and including firewood. He also included some assessments in the modifications to wood burning equipment efficiency and safety and finally the impact of wood combustion on air quality. He indicated some ways to regulate this area would be through standards, interaction with the community, regional type of interaction, and interaction with the industry.

Dr. Hornig's discussion--paper--was about an air quality test in a small town in New Hampshire. What is important is that he used a technique on the polycyclic organics to develop a fingerprint of the wood emissions. What was concluded was that it is necessary to develop an oil burning fingerprint in order to separate oil burning equipment emissions from wood burning equipment emissions. He also noticed a definite increase in the emissions and in the POM's during the wintertime as compared to summertime.

A paper I presented for Mr. Bendersky of Pyros was the result of a workshop which dealt with the emissions problem from wood burning stoves. It was the first time I heard of a meeting where a number of experts were assembled to smoke out some answers on wood stove emissions. The first step was to develop a standard on measuring wood stove emissions, and this is currently underway. The next is R&D on the pollutant formation of the wood stove versus the stove type. Before you can do this, you need to have an emissions measurement standard; then there is the needed R&D and finally air quality tests. As I said just prior to this, these things seem to be well in hand and we are progressing in these areas of priority.

A final paper--and I know this will be a brief review--was by Mr. Lim. He showed some data comparing the amount of emissions from both industrial and residential equipment. It is interesting to note that the industrial is lower than the residential. Table 1 will indicate why. This is a comparison of the two techniques. As you can see, the left part of Table 1 is the residential area and on the right part is the industrial area. The operation of the two can be seen as the next step. The residential operates in a starved air condition, meaning it is fuel rich--fuel rich meaning you will probably be putting unburned fuel up the stack as emissions; and this is indeed the case. Also the operation is intermittent. In the industrial type of process there is a very small amount of excess air. It is usually forced combustion and these operate on a continuous type of

TABLE 1. TYPICAL EMISSIONS FROM WOOD FIRED COMBUSTION[a]

Pollutant	Fireplace g/kg	Stove g/kg	Industrial Boiler g/kg
NO_x	1.9(0.85-7.7)	2.3(0.2-7.4)	0.8(0.1-1.2)
SO_2		0.2(0.16-0.24)	0.07(0.01-0.5)
CO	54(13-220)	150(10-420)	10(0.3-38)
Particulate	15(1.8-64)	13(1.3-45)	4.2(1.5-13)
Total Hydrocarbon	22(2.7-49)	25(2.0-110)	1.4(0.4-2.1)
POM	0.03(0.02-0.04)	0.3(0.01-0.4)	0.0006-0.027
Trace Elements		$\sim 10^{-3}$ or less	

[a] Emissions data compiled in Acurex Draft Report FR-81-85/EE, "Assessment of Emissions from Residential and Industrial Wood Combustion," by H. I. Lips and K. J. Lim.

basis. The air flow in a residential stove is vitiated, meaning it is oxygen starved; it is laminar, meaning the mixing between the fuel and oxygen is not good; and finally the mechanism of getting rid of your exhaust is buoyancy driven. In the industrial area the oxygen ratio is ambient, it is forced combustion, it is turbulent or well mixed; and the exhaust process is forced or driven by an exhaust means. The flame in the residential area is diffused and low temperature, which is a smoldering type of fire not normally found in the industrial process. In the industrial wood burning process the fuel and air are premixed meaning that there are high amounts of turbulence. There is a visible flame which is used to combust the emissions or to break down potential emissions. Finally, the heat trends in residential areas is direct, meaning it is like a radian stove while the industrial process uses a heat transfer fluid; a secondary means such as water. All these are indicated in Mr. Lim's paper. It is well known that industrial processes have fewer emissions than the residential process. That terminates the review of Session 1. Are there any questions?

Q. What is the net efficiency of the wood combustion process with the wood stove compared to the commercial application for net efficiency for transfer of heat?

A. In the wood stove normally there is a limit at the high-firing rate on how fast you can get rid of the heat, which means the flue gases are warmer or hotter than they should be. When you run a stove flat out, its flue gas temperature is 800 degrees or so. In industrial boilers the flue gas temperature is normally about 300 and something degrees for an efficient unit. Does that answer your question?

Yes.

Q. Do you know if any research has been done on relative levels of POM's, PAP, anything that is required to produce carcinogenic effects? Is there any idea whether these things in current concentrations are anywhere close to causing problems or do you know of anything there?

A. The answer is yes. The health effects lab in EPA is currently doing research in this area. Benzopyrene is the constituent of cigarette smoke which is so dangerous and that is the one that has been referred to here several times. Jack Allen referred to levels of benzopyrene in measurements that they had made. It is not the only carcinogen; it is just one of all of the POM's, it is one of the most active and one of the most widely known. The Ames test is commonly used to measure mutagenicity and there are a whole series of bioassay tests: Chinese hamster ovary is another common test that is used. There are whole animal tests that are used and so the answer is yes. Work is being done to determine the effects and they have definitely found effects. I should add that polycyclic organic matter is not necessarily the only bad actor. There are other compounds which we are beginning to look for that the health effects people feel could be a lot worse. The general category is nitroarenes; and this is a compound which is not extremely stable--in a couple weeks period, it will break down to an amine. In the form of a nitroarene, it is extremely reactive.

Q. Regarding the levels of saturation in the atmosphere of the test animals, is that anywhere close to what we might get in an environmental situation--levels of testing, as far as exposure to test animals? Are those levels of exposure anywhere close to what we might get in a regular environmental situation today in a worse case?

A. Yes, they are. In other words, you are thinking of the cartoon where they stuff the rat so full of whatever it is, he blows up before he gets sick. No, they are not doing that kind of testing. They are exposing the animals and doing the test at fairly low concentrations. For example, on the Ames test that they ran on the stove that we tested in our lab--the one I had hoped to report on here at this meeting but have not gotten the data back yet so I could not write the paper--the initial tests had to be repeated at a lower concentration because the normal first run that they made was so toxic that their specimens were completely wiped out, and they are having to repeat the test at lower and lower concentrations to get a decent curve. So the tests are being done at meaningful levels.

Q. Related to that, the gentleman from Dartmouth on that study in New Hampshire talked about his fingerprint pattern. I was wondering, is this--does this relate to any other fingerprints that have been established in wood combustion? Was he taking a known pattern or is that still being discovered? And how did that relate to other fingerprints of other fields? He was talking about, I think, the particulates.

A. I think it is appropriate that Dr. Hornig answer that question.

A. The fingerprint I had shown was simply the 10 POM's in highest concentration and showed the relative concentration of them. As far as how it compares with other combustion of other fuels, one of the things we had looked for was a difference in that fingerprint between a town where wood was the predominant fuel and another town where there were substantial amounts of oil. We did not see any difference between the fingerprints. That is not quite conclusive because the location of the sampler and such things would have to be understood but it does not look likely as though that kind of fingerprint will easily tell the difference between oil and wood.

Bob, I think some of these questions concerning health effects go to the very heart of the matter; and the reason for our being here in the first place. I do not know a lot about that area myself but I do know one piece of information that I thought might shed a little light on the question. The EPA has responsibility under the Clean Air Act to establish national emissions standards for hazardous air pollutants. BAP (benzoapyrene) is one such pollutant that has been number one, classified as a hazardous air pollutant, and; number two, an emissions standard. A national emissions standard for BAP has been established for coke oven emissions. That certainly is not directly in line with what we are talking about here but it does provide a point of reference from which we could relate the emissions of BAP from wood combustion to what the agency has already established as a standard for BAP emissions. To add to that the health effects group is putting together a paper comparing a variety of sources: coke oven emissions, wood stoves, residential oil heating, diesel exhaust from automobiles, and a number of other emissions. If everything goes as planned, this data will be presented in June at the John Cooper meeting in Oregon.

I would just like to call the audience's attention to the fact that there is a new journal called "Nuclear and Chemical Waste Management" which is published by Pergamon Press. Only the second number of it has appeared so far, and its scope is still developing, but I have invited one of the contributors to these sessions to submit his contribution to the journal. I am one of its co-editors, and I would like to encourage others who are working in this field to consider that as a journal for the submission of scientific material. It is a referee journal and we hope to make it an absolutely first-class scientific medium for the dissemination of basic information with respect to waste management. Let me append to that, that there is no substitute for referred journals as sources of solidly reliable information. Other types of publications may be useful and have certain value but I think we must recognize that magazines, for example, which publish purely anonymous material as Consumer Reports does, for example, cannot be considered to be on a par with referred scientific publications.

Thank you.

Thank you, Hank.

HIGHLIGHTS FROM SESSION 2 - ASSESSMENTS OF RESIDENTIAL WOOD HEATING EFFICIENCY AND EMISSIONS

by: Jerome P. Harper
Supervisor, Solar Test Facility
Solar Applications Branch
Tennessee Valley Authority
Chattanooga, Tennessee

INTRODUCTION

The papers presented during Session 2 covered a wide range of topics. Investigations on the effects of altitude on wood heater emissions, controlled laboratory efficiency and emission studies evaluating the effects of fuel type and measurement techniques, field studies evaluating wood furnace performance, and current research on the subject of indoor air quality and wood heater use were presented. In the following summary, both the experimental approach and results of each study will be highlighted. This summary will progress from laboratory studies to the field studies.

MRC HIGH ALTITUDE STUDY

The purpose of the Monsanto Research Corporation study was to identify any differences which existed between wood heater emissions at high altitudes versus low altitudes. The study was funded by the EPA and had the support of many mountain state environmental agencies, particularly Colorado, which noticed very high levels of wintertime particulates in resort areas. The study was done at Colorado State University and utilized exactly the same equipment and the same test fuel as a similar study done at Auburn University at a lower altitude by Monsanto Research Corporation the previous year. The basic design of the wood heater used was a radiant baffled system.

The conclusion from the Monsanto study was that no significant difference in emissions, either particulates (EPA Method 5) or carbon monoxide (CO), were seen at high altitudes versus those at lower altitudes. The data presented did show a slightly higher level at elevated altitudes than the lower altitudes for particulates (.5788 gr/dscf vs. .3249 gr/dscf at low altitudes) and slightly lower CO levels (181 g/kg vs. 230.5 g/kg at low altitudes). These differences were not determined to be significant and the variation is mainly attributed to the difference between the ambient air temperatures in the high altitude test, 49°F, from that in the previous low altitude test, 70 to 75°F. This temperature difference was stated to have important effects on the combustion process by cooling the flame and slightly increasing particulate emissions.

CCRL EFFICIENCY AND EMISSIONS TESTING

Details on wood heater efficiency and emissions testing activities being conducted by the Canadian Combustion Research Laboratory in Ottawa were presented. Data for a number of different types of systems, side draft, down drafters, fireplaces, and furnace add-ons, were discussed. Efficiency was determined by the indirect or stack loss method. Continuous instrumentation was utilized during the test to measure flue gas composition. Carbon dioxide, carbon monoxide, oxygen, hydrocarbons, and nitrogen oxides were measured.

Four points were made on test methodology. The continuous monitoring approach was considered to be necessary for wood heater efficiency and emissions testing because of the transient or nonsteady state burning that occurred. Therefore, wet orsat or grab-type sampling was not an adequate approach for sampling flue gas from wood heaters. Secondly, the measurement of hydrocarbons is very important for both emissions and efficiency determinations. Current efficiency calculation approaches tended to estimate this parameter on the basis of a carbon balance rather, than measuring it, and to assume the hydrocarbons are methane. Third, the size of the test fuel utilized is important. One CCRL study evaluated the use of brands versus 4" triangular sections of wood. Differences in the efficiency curves between brands and 4" triangular sections were significant primarily because of the large increase in CO emissions which occurred when brands were used resulting in higher emissions and lower efficiency. Brands were not recommended for use in either efficiency or emissions tests. The fourth point was that efficiency and emissions are interrelated such that as efficiency increases, emissions decrease.

Other conclusions resulting from CCRL research were that well designed side draft stoves have a greater potential for higher efficiency and reduced emissions than other types of stoves presently available, that the horizontal baffle appears to offer the next best overall performance, that the available down drafts offer little performance advantage over even the poorer up draft types, that fireplaces are very inefficient, have higher emissions per heat output and that a negative energy benefit can arise, and that the performance of a specific stove model depends primarily on how the design uses potential performance advantages of its type, such as refractory, air mixing, or baffling.

ANL LABORATORY TESTING

The studies conducted at Argonne National Laboratory strove to obtain a real world type of measurement for wood heater operation from the viewpoint of efficiency, creosote formation, and particulates in the gases. A basic radiant baffled wood heater was used. The Argonne study conducted their measurements under near steady state burn conditions. Measurements were not made on the wood heater system until after the initial transient burning phase, approximately 30 minutes, had taken place. Contrastingly, CCRL did their studies over a complete burn cycle. Efficiency and flue gas velocity flow rate were estimated from the CO and CO_2 measurements. Oxygen was not a parameter measured. The Argonne study utilized two types of test fuels, a small log approximately 3" in diameter and larger logs approximately 6" in diameter.

The main results by Argonne are based on interpreting their efficiency data and emission data (CO, particulates, and creosote). One point made was that ANL did not observe any difference between the larger and the smaller diameter logs as they related to efficiency versus burn rate. Other differences were observed between efficiency and emissions. For example, CO emissions, when going from a low to a high burn rate (which corresponded to going from a low to high efficiency), tended to drop off. Therefore, the relationship ANL established for CO was that a wood heater operating at a relatively low efficiency, had higher emissions of carbon monoxide than when the stove was operating at higher efficiency. For particulate and also creosote emissions, however, another conclusion was made. Namely, that as the efficiency increased, the particulate emissions likewise increased and increasing creosote level with increasing efficiency was also observed.

IMR - WOOD FURNACE DEMONSTRATION

This study was on a field demonstration of wood-fired furnace systems conducted by the Institute of Man and Resources, Prince Edward Island. Ten different wood-fired furnace systems were investigated varying from the more advanced systems to the more conventional systems. A wood-fired furnace was designated as an advanced system if it had a forced draft, modern automatic controls, automatic feeds, or capability to take chips or pellets. All the conventional systems took only round wood as the fuel.

The efficiency of the systems was determined on an energy output/input type of analysis of the furnaces in the field. Input Btus were calculated on the basis of the amount of wood that was burned over a specified period of time (e.g. days, weeks, or months) and its lower heating value. The output was measured on the basis of flow rate and temperature of the particular medium. For example, for boilers, a Btu meter was used, while for forced air systems, temperature readings and a fan timer were used to estimate air flow rate after calibration of the fans. It was stated that this approach did not account for standing losses that furnaces exhibit and therefore, efficiency estimates are somewhat lower that may be expected.

Emission studies were also done for CO, NO_x, SO_2, particulates and creosote. Creosote was characterized by two factors; the heating value of the actual flue deposit and the amount of deposition in the flue (e.g. light or heavy). Particulate measurements were made with a high volume sampler.

The general conclusions of the study was that the more advanced systems typically had higher efficiencies and lower emissions. Efficiency of the units ranged between 24 to 49% in the winter, and 7 to 56% in the spring. Particulates ranged from .63 to 38.60 g/kg, CO from .9 to 161.9 g/kg, NO_x from .17 to 3.17 g/kg, SO_2 from .1 to .81 g/kg, and condensable organics from .2 to 12.59 g/kg. Generally systems with lower particulate and CO emissions had fewer chimney deposits. A significant design factor identified with reduced emissions was the presence of a preheater with a forced air combustion system.

GTI INDOOR AIR QUALITY STUDY

The final paper presented during this session was on a new topic in the wood heater emissions area, namely indoor air quality. The paper presented results of a study in Boston conducted by GEOMET Technologies, Inc. which evaluated the indoor air quality in a number of residences. Of the more than 30 homes surveyed in Boston, 2 had a fireplace which was used regularly and 1 had a woodstove. These three residences provided the basis of this study.

Data was taken on indoor air quality on wood-burning and nonwood-burning days. None of the three homes tested had low air exchange rate; the range was from .68 to 1.24 air exchanges per hour. Atmospheric constituents measured were NO, NO_x, CO_2, CO, O_3, SO_2, CH_4, THC, TSP, RSP, and BaP. However, the study primarily concentrated on four major variables: total suspended particulates, respirable particulates, benzo-a-pyrene, and carbon monoxide. Carbon monoxide measurements were made continuously during the sampling period whereas the particulates and benzo-a-pyrene were integrated measurements over a specified sampling period.

Significant increases in air pollutants were observed on wood-burning versus nonwood-burning days especially in the older residences with higher air exchange rates. TSP was 1.8 to 5.6 times higher on wood-burning days than on nonwood-burning days and RSP 1.4 to 10.3. Of the gases measured, BaP concentrations were nearly five times the urban national ambient average. Wood burning had its greatest gaseous impact on the CO level which ranged from 0 to 6 ppm. It was stressed however, in the paper that these results are very preliminary, for example, one of the residences had only one data point.

Operation of the woodstove was shown to be very important in affecting emissions inside the homes. The CO emissions profile obtained during the sampling period illustrated that high carbon monoxide levels in the homes could be associated with periods when opening the stove, loading fuel, or stoking the fire occured. In all cases in the study, indoor levels of the particulates measured, tended to be much higher than the outside levels. It was stated during the presentation that local micrometeorology may be a very important factor related to indoor air quality and wood combustion. Total suspended particulate levels in the homes during wood-burning periods exceeded both primary and secondary National Ambient Air Quality Standards, whereas respirable particulates exceeded secondary NAAQS standards.

SUMMARY

The papers presented here span current research being conducted on the subject of wood heater efficiency and emissions. The studies illustrate the need for both laboratory and field studies to refine our understanding of wood heater design, operation, and fuel properties so more highly efficiency and less polluting devices can be manufactured.

Session 5: PANEL - ISSUES RELATED TO THE RESIDENTIAL COMBUSTION OF WOOD AND HOW THEY MAY BE RESOLVED

Chairman: Michael C. Osborne
U.S. Environmental Protection Agency
Research Triangle Park, NC

COMBUSTION OF WOOD/ENVIRONMENTAL RESTRICTIONS IN SWEDEN

by: Jan Nilsson
The National Swedish Environment Protection Board
P O Box 1302
S-171 25 SOLNA, Sweden

ABSTRACT

The emission of organic compounds from wood combustion in stoves and furnaces is fairly high. Emissions determined as average values during sampling periods of two hours in a Swedish study for dried wood in closed fireplace ovens were

Ethene mg/kg, dry fuel	16-3800	(momentary samples)
Benzene mg/kg, dry fuel	30-1600	(" ")
Benzo(a)pyrene µg/kg, dry fuel	27-3300	
PAH, sum of 22 species, µg/kg, dry fuel	5100-9600	
Chlorobenzenes, µg/kg, dry fuel	24- 80	
Tetra- and pentachlorophenols, µg/kg, dry fuel	160-2200	
Mutagenicity (Ames) revertant/g dry fuel	330-2200	

The use of raw wood gives emissions of organic pollutants about 10 times higher.

Recommendations on restrictions on the use of residential wood combustion are presented. Being interimistic they will be applied until the final version has been worked out.

AUTHORITIES AND LEGISLATION IN SWEDEN

Environmental decisions on wood combustion in Sweden are made by various authorities according to some different legislations. A short review of these will be given in order to make it easier to understand the further statements.

The most important authorities are

- The National Swedish Environment Protection Board, whose main task is to give guidelines and recommendations to other authorities.
- The National Swedish Franchise Board for Environment Protection. Conditions for acceptable emissions from separate major plants are laid down.
- County administration. There are 24 counties in Sweden. Each of these has an environmental administration working with environmental planning. The environment administration issues permits with specific conditions for

separate plants, and is the supervisory authority of activities hazardous to the environment within the county.

- Municipal administration. In each municipality there is a small environmental administration. There is a trend in Sweden to turn over a greater share of the responsibility for the environment to the municipalities.

The most important legislations concerning combustion of biomass are

- The Building Act
- The Environmental Protection Act
- The local public health by-law

INSTALLATIONS CONCERNED

On October 1st, 1980, there was a change in the Environmental Protection Act to the end that the combustion of biomass was included in the legislation. Briefly the following applies:

- Installations with a energy input larger than 300 MW are not allowed without the permission of the Franchise Board for Environment Protection.
- Installations with a energy input between 10 and 300 MW must not be constructed without the permission of the County Administration.
- The permit rules of the Environmental Protection Act is not applicable to installations under 10 MW. Normally, these types of installations are regulated according to the Swedish building code. Today this lacks instructions on wood combustion. A committee with participants from the National Swedish Board of Urban Planning, the Environment Protection Board and the National Swedish Board of Health and Welfare has started the work of drafting a supplement on wood cumbustion to the Swedish building code. Until this work has been completed, which will take at least one year, the recommendations given by the Environment Protection Board will serve as guidelines (see below).

GUIDELINES, NON-RESIDENTIAL INSTALLATIONS

As has been mentioned earlier biomass has recently been included in the Environmental Protection Act. The Government has not yet formally established the guidelines according to this law. It is a time consuming process to do the work of unravelment. Therefore, the Swedish Environment Protection Board will give recommendations to the County Administrations. These recommendations will probably apply to

- Installations larger than 10 MW. The performance standard for dust is 55 mg/MJ fuel. This corresponds to about 100 mg/m^3 norm dry gas at 10% CO_2. To attain this it is necessary to set up electric precipitators or bag house filters.
- Installations smaller than 10 MW. The performance standard for dust is 165 mg/MJ fuel, which corresponds to about 300 mg/m^3 norm dry gas at 10% CO_2. To attain this multicyclones can be used.

When setting the performance standards technical and economic aspects have been taken into consideration along with environmental assessment. Dust emissions may create annoyance through pollution. The content of heavy metals is fairly high, especially in some types of biomass. Emissions of POMs are high, at least from small plants. Heavy metals as well as POMs are mainly adsorbed on particles.

The stack height shall be chosen so that the guidelines set by the WHO expert group for NO_x are not exceeded. There are no plans on performance standard for NO_x from wood combustion at present. The sulphur content of wood is low.

RECOMMENDATIONS, RESIDENTIAL COMBUSTION

Investigations have shown high emissions of POMs from residential combustion in stoves and furnaces. The Swedish results are in good agreement with the data presented at this conference.

The National Swedish Environment Protection Board will soon give recommendations to the municipal authorities on residential wood combustion. These recommendations are provisional and will apply until formal stipulations are included in the Swedish building code. They are not yet officially decided upon, but the probable content will be

- No restrictions on open fireplaces.
- Wastes must not be burnt.
- Stoves should not be permitted if the distance between the chimney and the neighbouring house is less than about 25 m. If many stoves are to be installed in a new residential area more stringent restrictions ought to be applied. Areas with bad meteorological conditions may also induce special restrictions.

Some important arguments put forward when formulating these recommendations will be mentioned. The concentrations of organic substances in the neighbouring house may be high, if the building has ventilation with separate air intake. Meteorological calculations have shown that there will be a dilution factor of about 1000 at the air intake point if the distance between the houses is about 20 m. Under bad conditions dilution will be only 300-400. These values are based on short-term (one hour) measurements and relate to burning in one single unit. In a residential area with a general use of stoves the ambient air quality will have a dilution factor of 3000-5000 as a long-term value.

The most critical substances in emissions from wood combustion seem to be PAH, benzene and perhaps ethene.

Using a dilution factor of 1000 the ambient air concentration of benzo(a)-pyrene from one stove will be about 900 ng/m^3 in an area within a radius of about 30 m, if the highest emission value measured in our studies is used. A more typical value is about 10-20 ng/m^3. The corresponding values for benzene are 3-150 µg/m^3. Normal ambient air concentrations "above roof" in the central parts of a city are 3-6 ng/m^3 benzo(a)pyrene (yearly average) and 10 µg/m^3 benzene.

It is not only benzo(a)pyrene which will give high ambient air concentrations. The same is valid for a lot of other POMs.

Available data indicate that the content of inhalable particles is rather high in smoke from wood combustion.

FURTHER MEASURES

The recommendations given by the Swedish Environment Protection Board are not compulsory to the municipal authorities. In about 15 towns restrictions are already implemented. Based on the density of houses and the meteorological conditions the densely populated area is divided into areas where

a) new stoves should be avoided

b) the installation of new stoves should be restricted

c) no specific restrictions are needed

The manufacturers of stoves are now trying to create better combustion conditions and to take other steps in order to decrease the emissions of POMs. A crucial point seems to be to decrease the content of carbon monoxide as it seems to be correlated with the emissions of PAH (Figure 1). The relationship between the results using the Ames salmonella test and the content of carbon monoxide also seems to be fairly good (Figure 2). This development is supposed to result in decreased emissions. Hopefully it will be possible to introduce a system of "model approval" in the Swedish building code, which at least partly could replace the more general recommendations now presented.

RESEARCH

To get a better foundation for the final regulations more research will be initiated in the next years. This will be done in close cooperation with the other Nordic countries. Areas of interest are

o Characterization of emissions from wood and peat-fired plants.

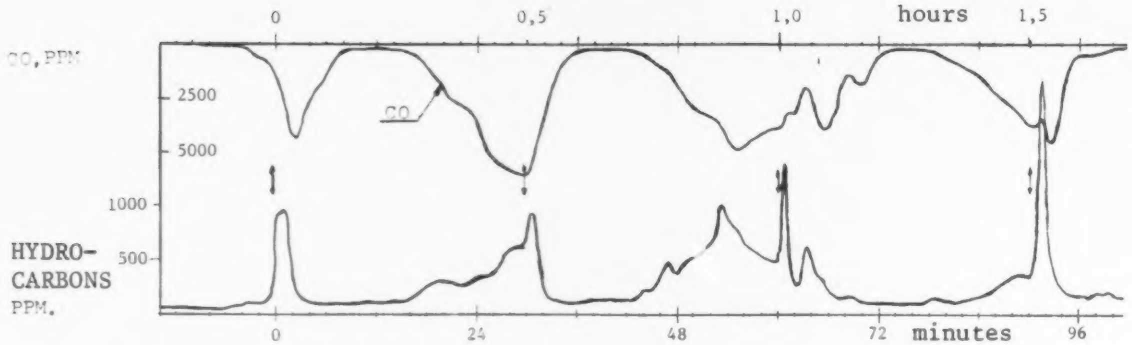
o Development of a method to charaterize the emissions of POMs without using a complete analysis. Can the quotient CO/CO_2 be used for the model approval of stoves?

o Emission control techniques for wood and peat-burning.

o Ambient air assessment in urban areas where wood is the predominant fuel.

o Transformations of PAH in the atmosphere.

Corresponding studies are undertaken for coal and oil-burning in Sweden in the project Coal, Health, Environment.



↕ = Feeding with wood

Figure 1. Continuous registration of CO and total hydrocarbons (Rudling et al 1980).

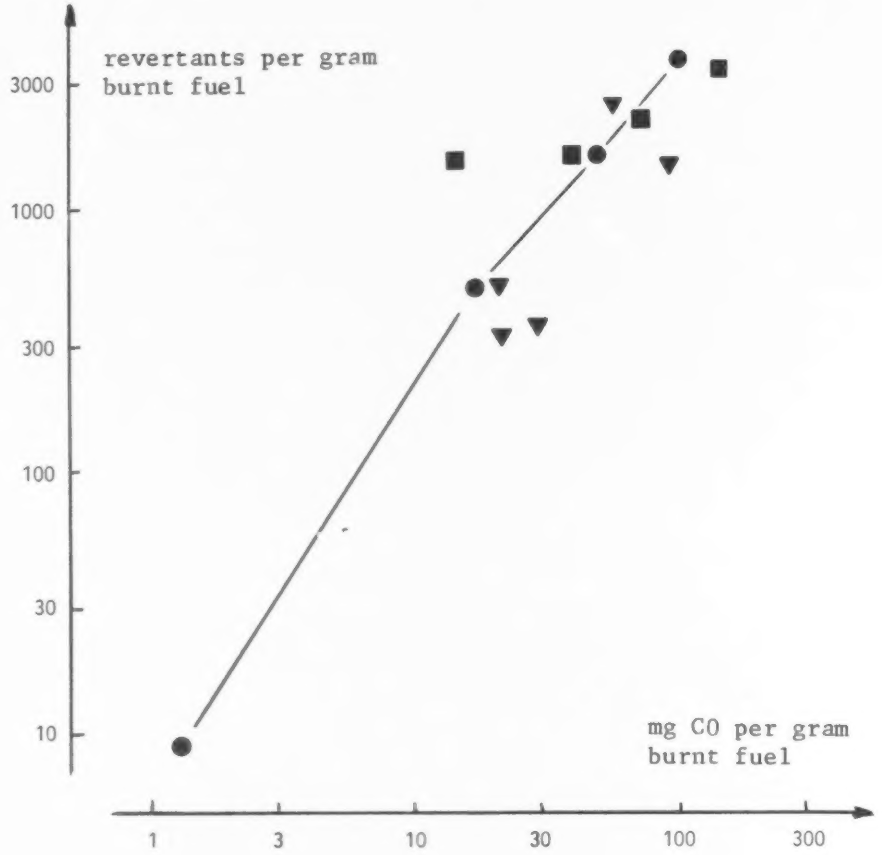


Figure 2. The correlation between emissions of CO and mutagen activity, measured as revertants in the Ames Salmonella test (Rudling et al 1980).

REFERENCE

Rudling, L et al (1980). Chemical and biological characterization of emissions from combustion of wood and wood-chips in small furnaces and stoves. The Swedish Environment Protection Board PM 1331. 79 pp (written in Swedish).

INSTITUTIONAL AND REGULATORY APPROACHES TO CONTROL RESIDENTIAL WOOD BURNING EMISSIONS

by: W. T. Greene and B.J. Tombleson
Oregon Department of Environmental Quality
Portland, OR 97207

ABSTRACT

After an introduction on the severity of pollution impacts from residential wood heating in Oregon, different potential institutional and regulatory approaches to control pollution from this emission source are discussed. Approaches include performance rating certification programs, programs which certify compliance with standards, weatherization programs to reduce heating needs, educational programs, governmental efficiency/emissions/ safety inspection programs as in West Germany, and government or trade association research programs to develop improved emission control techniques. The importance of developing a simpler, yet repeatable, emissions measurement method is emphasized.

INTRODUCTION

Alice: Would you tell me, please, which way I ought to go from here?
Cheshire Cat: Well, that depends a good deal on where you want to get to.
Alice: I don't much care where. . . . .
Cheshire Cat: Then it doesn't much matter which way you go.

Residential wood combustion is at a crossroads of sorts. After the rapid resurgence in stove sales over the last 10 years, evidence is mounting that residential wood combustion can cause significant air pollution problems in areas where wood usage is relatively concentrated. One crossroad for the manufacturers of these devices is to decide whether they intend to modify the design or operation of these heating units so that particulate (smoke) emissions are substantially reduced, and if so, how the industry as a whole can best move towards that goal.

Evidence from Oregon is substantial that residential wood combustion (RWC) can cause significant particulate air quality impacts. In Medford, Oregon, 24-hour respirable particulate (< 2 u) impacts of 82 ug/m^3 from RWC have been recorded during winter poor ventilation conditions. This impact was determined by chemical mass balance analysis (chemical fingerprint tracing techniques). Such an impact is definitely significant in light of the fact that it is all fine particulate and the 24-hour ambient standard for impacts from all sources is 150 ug/m^3.

At a downtown Medford, Oregon site, annual average impacts of 20.6 ug/m^3 of respirable particulate from RWC were recorded for the July 1979 to June 1980 sampling period. This impact amounts to 66% of all the locally generated respirable particulate and 29% of all the locally generated total particulate and is clearly the emission source category with greatest impacts. *

In the Portland, Oregon area, with a metropolitan area population of about one million, 24-hour impacts of 35 ug/m^3 ** from RWC were identified by Carbon 12 vs. Carbon 14 dating techniques during a January 1978 day which exceeded standards. Annual impacts at the maximum impacted site in 1977 were estimated through modelling to be 3.7 ug/m^3 and have been projected to be 9 ug/m^3 by 1987 if present trends continue. Residential wood combustion emissions in the Portland area now exceed all the particulate emissions from industry in the Portland area. ***

Evidence from Oregon and other locations indicate that pollution impacts from residential wood burning are a significant problem which will pose some constraints on the continued expansion of wood as an acceptable residential heating fuel. The need for some technological or operational improvements to reduce adverse impacts from traditional sources like autos or industry is quite common in industrialized societies and has been dealt with rather effectively. Wood heating control has gone virtually untouched to date. In the following discussion several different institutional and regulatory approaches are discussed which have been used or are being used to deal with analagous problems. As the reader will discover, almost all of the different approaches rely on some performance rating scheme to allow relative evaluation of equipment modifications or performance.

---

* Vegetative burning sources were determined to have an annual average impact of 21.4 ug/m^3 at this site in the Medford Aerosol Characterization Study Report, February 1981, by the Oregon Graduate Center. Other vegetative burning source impacts such as from open burning were determined by modeling to be .8 ug/m^3, resulting in a 20.4 ug/m^3 impact for residential wood burning.

** "Environmental Impact of Residential Wood Combustion Emissions and Its Implications", Dr. John A. Cooper, August 1980, JAPCA, p. 856.

*** Oregon State Implementation Plan for Total Suspended Particulates for the Oregon Portion of the Portland-Vancouver Air Quality Maintenance Area, 1980.

OVERVIEW OF INSTITUTIONAL AND REGULATORY APPROACHES TO CONTROL RESIDENTIAL WOOD BURNING EMISSIONS

Numerous different institutional or regulatory approaches might be used to control residential wood burning emissions. Discussed below are several of the approaches, which are either in use now, or which have been used in similar situations. These include:

- Performance rating programs
- Certification programs for determining compliance with standards
- Incentive programs for equipment replacement
- Inspection programs as in West Germany
- Education Programs
- Weatherization Programs
- Research programs

CERTIFICATION PROGRAMS

Several different types of certification programs are possible including simple performance rating programs, and programs which certify compliance with standards. Performance rating systems can be sponsored by either a government agency or by a trade association for the equipment manufacturers.

Government agencies generally prefer that certification programs be developed by those firms who produce or use the particular appliance or equipment that needs certification, but agencies will occasionally develop certification criteria and require products to meet them when an urgent need exists.

Performance Rating Programs

One of the most successful examples of a trade association certification program is the program of the Air Conditioning and Refrigeration Institute (A.R.I.). Over 180 different companies belong to the ARI and 160 of these firms produce products which are performance rated and certified under A.R.I. test programs. Members pay dues which support some staff and engineering committee meetings. The Engineering Committee has developed 60 industrial standards which relate to the performance and safety of air conditioning and cooling equipment. *

The A.R.I. certification programs cover 33 major different product areas with sub-model breakdowns in addition. Testing costs range from $600 minimum to as much as $40,000 per year for some of the largest

---

* Specifying Engineer, November 28, 1978 Supplementary Issue, "A Look at the ARI", p. 26.

manufacturers with as many as 15 different products. The certification programs are all voluntary, rigidly enforced, and are based on one or more standards developed by the various engineering committees. A seal of certification is awarded for all product lines which meet specifications, and an annual Directory is published and distributed by A.R.I. which lists the certified equipment by manufacturer, by model type, and by model number. Certified capacity ratings, power consumption, and energy efficiency ratios are also presented.

The benefits of a trade association certification program are many. They include the fact that the manufacturers of equipment must cooperate with each other to determine the appropriate standards of performance, the fact that knowledgeable individuals within the industry with hands-on equipment experience can develop the standards, and the recognized fact that groups of individuals can police themselves more effectively if they are motivated, than an outside group, for example a government agency.

The energy efficiency of many of the units tested under ARI programs increased fantastically during the period of 1970 to 1980. In ARI's January 1976 Directory, only 37% of the units sold had an energy efficiency rating of 7.0 or better. In the January 1981 Directory, over 65% of the units sold had an energy efficiency of 7.0 or better. Although some of this improvement probably would have occurred even without a certification program, it is clear that much of the credit must be placed on the fact that a published document was available to all major equipment purchasers which showed which products met safety standards and what the energy efficiency ratio was for each model tested. Clearly, with good information, a purchaser will select the equipment with the best ratio of performance to cost.

Programs Certifying Compliance With Standards

On some occasions, government agencies perceive there is a need for a certain level of equipment performance which is not being met by private industry, and they will thus establish standards for equipment, and require certification of compliance. Examples of this type of program include EPA's fuel economy testing program for motor vehicles which is linked with the Department of Transportation's fuel efficiency standards for automobile manufacturers, and Great Britain's certification program for "smokeless" (reduced-smoke) coal fuels and coal stoves.

When EPA's fuel economy rating program began in 1973, the fleet wide average fuel economy was 14 miles per gallon. Now, in 1981, after fuel economy performance ratings have been available for eight years, fleetwide average fuel economy is 22 miles per gallon, for a 57% increase in 8 years. This progress has been made despite the claims that the EPA rating procedure often overstates fuel economy.

It is not clear how much of the efficiency gain has been due to D.O.T. standards versus consumer feedback demanding more fuel-efficient cars. Undoubtedly both factors have contributed. What is important is that a yardstick has been available by which the relative fuel economy performance of cars can be compared. Consumers selecting new cars have given car manufacturers consistent feedback that they prefer better fuel economy and that message has shaped the direction of automobile designs to a great degree in recent years.

Great Britain's coal certification program was instituted in 1956, four years after the famous 1952 London "fog" episode during which 4,000 deaths occurred which were attributed to the high sulfur dioxide and particulate pollution from residential coal burning. In 1956 a three-pronged program * was established in which:

- smoke control areas were established for dense urban areas with heavy coal burning.
- residential coal burning which produces smoke was prohibited in smoke control areas and burning allowed only with smokeless coals or smokeless stoves (as rated by specific British standards).
- a 70% rebate program for coal stove users was set up with government subsidy of 70% of the cost of a clean burning replacement coal stove (see next section).

After clear recognition of the scope of the residential coal burning problem in 1952, English researchers developed some coal-based smokeless fuels by 1956. This allowed the government to adopt the programs outlined above (1956 British Clean Air Act) because reasonable alternatives were provided. Initially only certain coal fuels which were determined to be "smokeless" (low-smoke) were allowed to be burned in the smoke control areas. Coals were considered to be "smokeless" if the emission rate as measured per British Standard 3841 by an electrostatic precipitator (ESP) at the top of the chimney stack was less than 5 grams/hour (for an average burn rate of about 2 pounds/hour with refueling at 1-1/2 hour intervals). Since 1956, a method has been developed which allowed the emissions rate evaluation for coal-burning stoves (Recommended Method PD6434 in 1964) based again on collection of particulates with an ESP. So that different units could be compared in an equitable manner, the standard was set at 5 grams/hour with one additional gram/hour allowed for each 10,000 Btu/hour of useful heat output. **

---

* Clean Air Today, British Department of Environment, 1974.

** 1-20-81 Phone Conversation With R.C. Payne, National Coal Board.

Although an ESP method of measuring particulates from coal is not perfect, because much of the condensible organic vapors will not be captured while in a volatile state, the method provides a useful and consistant mechanism for appraisal.

Since the 1956 British Clean Air Act was adopted, more than 15 different types of coal-based fuels have been certified as "smokeless" and more than 11 different types of coal stoves have been certified as "smokeless". *

The testing of these coal fuels and stoves is conducted by a British nationalized firm, the National Coal Board. The testing of fuels under B.S. 3841 is relatively simple compared to the stove testing; costs will normally run about $500 for testing a specific coal for its emission rate in a typical stove. The testing of stoves is considerably more complicated because 5 tests are conducted at each of three output levels: maximum, intermediate, and minimum. A screening test with 1 coal type will typically require about 90 man-hours of testing and cost $2400. A more complicated testing in which 2 coal types are evaluated will typically require about 250 man-hours of testing and cost about $6200. For units to be certified for each of Britain's six types of coal, about 600 man-hours of testing are needed at a cost of about $15,600. *

"The British program has achieved some good measure of success. For example, December sunshine in London is now 70 percent greater than twenty years ago, while on an average winter's day visibility is 4 miles (instead of 1 1/2 miles, as formerly). There is also a greater variety of plant and bird life and this, together with savings in labor and expense on laundry and house cleaning, has undoubtedly made life pleasanter." **

The lessons that can be drawn from the British program are several. The first and foremost of these is that a performance rating feedback scheme and standards, even if an imperfect measure, can enable significant technological improvements to occur in a relatively short time.

The 70% replacement subsidies were undoubtedly critical in replacing so many poor combustion stoves with other fuels or stoves, but the replacement program could never have occurred unless there was a means for evaluating which stoves and fuels burned relatively cleanly and which produced relatively large amounts of smoke.

---

* 1-20-81 Phone Conversation with R.C. Payne.

** Clean Air Today

Inspection Programs

West Germany has a home-heating device inspection program whereby residences are inspected twice per year for heating unit deficiencies in the areas of safety, emissions, and efficiency. These "master chimney sweeps" or "Schornsteinseger" as they are called complete a several year apprentice program before they are rated as master sweeps. During this apprentice period they become qualified in the areas of electricity, combustion, pollution minimization, furnace repair, efficiency determination, and safety analysis.

All residential fossil fuel heating devices and chimney flues are inspected twice per year by a Schornsteinseger and an analysis is conducted of whether the unit is operating safely, whether flues need cleaning, whether the unit is operating efficiently, and whether excessive smoke is being produced. Any deficiencies must be corrected by the homeowner or occupant within 30 days or a penalty on the order of $50 can be incurred.

Many individuals have contended that no program will ever be acceptable in the U.S. which authorizes government entrance and inspectors in homes. This program is cited not so much to advocate it as the best solution, but to point out that other countries, similar in socio-economic status to the U.S., have been able to obtain political support for a program in which government inspectors often inspect homes and can require heating system maintenance or modification to meet each of the goals of safety, low emissions and reasonable energy efficiency.

INCENTIVE PROGRAMS FOR EQUIPMENT REPLACEMENT

If the performance of a particular type of equipment is judged by a government agency to be critical, incentive programs are sometimes adopted to speed the replacement of the poorly performing equipment with a more satisfactory version. Britain's lawmakers viewed the hazard from dense coal smoke to be of such concern in 1956, that the British Clean Air Act authorized the direct subsidy of 70% of the cost of converting to a "smokeless" fuel heating unit. The central government contributes four-sevenths of the grant and the local authority three-sevenths. In cases of hardship, the grant may be up to 100%, at the discretion of the local authority. *

Air pollution offsets are another example of financial incentives to replace equipment. The permission to pollute with an approved permit is sometimes a critical element for operation of large manufacturing

---

* Clean Air Today

facilities in limited airsheds. In some airsheds, the dispersion capabilities of the atmosphere are so overtaxed, that new major air pollution sources are only allowed to build new polluting facilities if they find some similar sized pollution source and control those emissions to provide a greater-than-one-for-one offset for the new source (per EPA Emission Offset Policies). In some locations, companies will pay for the controls on other industrial sources and on some occasions, an older marginal firm will even be purchased and shut down to provide the needed offsets. Major pollution sources are sometimes motivated to such actions because the Clean Air Act as amended in 1977 places greatest restrictions on major industrial sources in limited airsheds and minimal or no restrictions on emissions growth from area sources such as space heating.

It is not inconceivable that some major industrial sources will find it attractive to obtain emission offsets by reducing residential wood burning particulate emissions by a widespread program for the replacement of residential heating devices with cleaner burning units. The concept becomes even more conceivable when it is realized that in some airsheds such as in Portland, the estimated residential wood burning particulate emissions exceed the particulate emissions from industry.

Tax credits can work well to effect a more rapid replacement of older capital equipment. In Oregon, pollution control tax credits are available for industrial sources in amounts up to 50% of the equipment purchase price. Since 1968, over 1165 separate tax credit proposals for industry have been approved with tax credits summing to $360 million. Although pollution tax credits to individuals have not occurred to date, analagous situations do exist. For example, during 1979 in Oregon, 25% tax credits were available on an energy conservation basis to individuals who installed fireplace insert heating devices in their fireplaces.

GOVERNMENT EDUCATIONAL PROGRAMS

Educational programs are sometimes utilized in an attempt to allow existing equipment to be operated as optimally as practical. Such programs have been used extensively in England in smoke-control areas and they are being used in Oregon to reach owners and operators of residential wood burning devices.

English Programs

In England, the government has established a Solid Fuel Advisory Service with branch offices throughout the nation. Each office has technical staff which can provide detailed information about smokeless fuels and appliances to homeowners.

Oregon Media Education Programs

In the Pacific Northwest, the Pacific Northwest Regional Commission

(PNRC), a regional division of the U. S. Department of Commerce which includes the states of Oregon, Idaho and Washington, has provided a $50,000 grant to the Oregon Department of Energy (ODOE) to develop a public education campaign on wood heating issues. Other agencies involved in wood heating education such as the Department of Environmental Quality (ODEQ) will assist in the planning process.

Although wood heating literature is available through the Cooperative Extension Services, this material is generally distributed to individuals who request specific information. Thus of the approximate 400,000 households who burn wood in Oregon, it is estimated that less than one-fourth of these households have obtained information about wood heating. Therefore, to facilitate better access to information, a series of public service announcements for radio and television will be produced in Oregon during 1981 for use in the tri-state area. Additionally a booklet detailing proper wood burning techniques has been developed for distribution in February 1981. The public service announcements will consist of two radio spots to promote the booklet and two sets of video and audio presentations to be released in Spring and Fall of 1981. The first of these will feature firewood selection and seasoning, and stove maintenance. The second series will be devoted to woodstove selection, weatherization installation, proper operation to minimize creosote accumulation and emissions, safety and efficiency.

A public relations firm has contracted to design and produce the television and radio messages in the form of interviews with people throughout the State of Oregon who currently use wood for their home heating needs.

This type of information exchange is believed to be the most effective in eliciting behavioral changes by gaining peer acceptance; the result will be an informative and educational approach for discussion of solutions to wood burning problems encountered in the Pacific Northwest.

Energy Extension Service Education Programs

The Oregon State University Extension Service is a joint cooperative educational service of Oregon State University, the U. S. Department of Agriculture and Oregon County governments. Extension offices are located in all 36 counties in the state, offering information on six program areas (agriculture, forestry, family living, community development, marine advisory and energy). The Oregon Energy program is part of a nationwide Energy Extension Service (EES) designed to encourage more efficient use of energy and adoption of alternative energy sources. This program began in early 1980, with funding provided by the U. S. Department of Energy to the Oregon Department of Energy via the Oregon State University Extension Service, who plans and conducts the Energy Extension programs within the state.

Current conditions, constraints, costs and benefits of utilization of forest residues and round wood for residential firewood as an energy source are addressed in the Energy Extension Program. Educational materials to date consist of a series of eight publications in the form of circulars or fact sheets that are available free of charge upon request to Oregon residents. These are: Heating with Wood: A Cost Comparison; Gathering Fuelwood for Home Heating; Burning Wood; Fuelwood Facts; Woodstove Selection; Installation of Wood Stoves; Chain Saw Safety; and Improving Fireplace Efficiency. Additionally, information on wood heating is made available at the County level through home energy fairs and public seminars at which Extension Service agents make formal presentations.

WEATHERIZATION PROGRAMS

Weatherization programs can reduce emissions by reducing heating needs. Generally if a percentage reduction in heating needs is achieved, annual emissions will be reduced by the same proportion. In 1977, the Oregon State Legislature passed several bills requiring energy suppliers to assist homeowners in conserving energy, mainly through weatherization actions to reduce the amount of fuel needed to heat residential dwellings*. The programs developed differ substantially among the suppliers, but all can work effectively to provide sufficient motivation to individuals to insulate and weatherize whereas they otherwise might not. Although the programs were developed to meet energy conservation needs, clearly the additional weatherizing done as a result of these programs can and does reduce emissions from residential space heating.

State sponsored low interest weatherization loans are financed through a commercial lending institution, terms vary depending on the individual bank or savings and loan organization. Services provided by the heating companies to help reduce home heating costs include: a free home energy analysis by an authorized representative of the company, technical advice on insulation materials and weatherproofing techniques, estimated costs and savings and assistance in locating registered contractors to perform the necessary work. Although the programs are very attractive, to this date only about 10 to 15% of electric company customers have taken advantage of it, and an even smaller fraction of the gas and oil company customers. Whether the homeowner insulates under the auspices of electricity, gas, or oil programs, owners of private homes, apartment houses, mobile homes with stationary foundations and houseboats are eligible for the low interest loans.

PGE Residential Weatherization Program

If a dwelling's primary source of space heating is from electricity, the resident can utilize the Portland General Electric (PGE) designed weatherization program to reduce energy consumption even if they heat with wood, so long as the dwelling has electric central heating fixtures. The program covers households in Northwestern Oregon.

---

* 1977 Oregon laws; Chapter 889.

This program is extremely attractive to homeowners because they can authorize as much weatherization for a dwelling as is cost effective, have the utility pay for all the weatherization, and never reimburse the utility until the dwelling changes hands. At the time of reimbursement, even if 10 or more years later, the utility is only repaid the original loan amount without any interest. While this arrangement is clearly attractive to homeowners it is even attractive for the utilities because kilowatts saved through this conservation practice are cheaper than kilowatts from new power plant generating capacity. To date, this program is only applicable to dwellings with electric space heating units installed prior to July 1978, but a 6 1/2% low interest loan is available to dwellings with electric heating installed after that date.

By calling a local PGE office an inspection can be scheduled with an inspector, who will recommend the necessary weatherization and explain the benefits to be accrued and their cost. The homeowner or renter has the option of doing some or all of the weatherization oneself, such as ceiling, floor, duct and pipe insulation and caulking and weatherstripping. "How to" information is provided by the PGE inspector, or with approval, PGE will arrange for a contractor to install the weatherization improvements. After completion of the work, the inspector returns to the home to survey the job completed and to collect the receipts for payment.

PP&L Weatherization Program

Pacific Power & Light offers a weatherization program quite similar in scope to the PGE program. An interest-free deferred payment loan is available to customers of single family residences, duplexes, condominiums or stationary mobile homes who have permanently installed electric heat in service on or before April 3, 1978. The company conducts a free audit to determine the retrofit measures that are cost effective and the loan is secured with a property mortgage requirement.

The low interest loan (6.5%) is available to customers who do not meet the no-interest eligibility criteria and to multi-family residential units with electric space heating. This loan has a 10 year maximum repayment limitation, has no cost effective criteria, but requires a promissory note secured by a lien and has specified amounts available according to the type of insulation installed.

A cash rebate incentive program has recently been added for PP&L customers for weatherizing their homes as an alternative to the above loan program. The rebate applies to a variety of energy conservation measures including installation of heat pumps and solar water heating systems.

The amount of rebate depends on the expected savings of kilowatt hours due to the improvements during the first year as determined by the company's home energy analysis. For example, an annual savings of 5000 kilowatt hours would quality for a rebate amounting to $325.00.

Northwest Natural Gas Residential Weatherization Program

Households that use gas as their primary source of space heating, including investment properties, are eligible to participate in the Northwest Natural Gas Weatherization Program. A consultant from the gas company comes to the home and conducts an energy-audit, determines what weatherization measures are needed, and the costs.

The homeowner may choose to do all or part of the suggestions provided by the gas consultant, they are then responsible for selecting a contractor for the work (must be Oregon licensed and bonded), submitting the estimated costs and a loan application. Approval of the loan is dependent on the party's credit rating. A homeowner may borrow up to $5,000 with a maximum ten year pay back at 6.5% interest. Monthly installments can be arranged at the rate of 1.1% per month per $1,000.

Oil Heat Companies

The weatherization program is coordinated through the Oil Heat Institute in Portland, Oregon. Many fuel oil dealers participate in a 6.% interest loan program available to customers who heat their homes with distillate oil. Maximum funds available range from $5,000 for a single family residence to $20,000 for a multi-family residence of nine or more units.

Weatherization Programs - City of Portland

The City of Portland adopted an Energy Conservation Policy on August 15, 1979. Energy planners estimate that successful implementation of all components of the plan will result in a city-wide energy savings potential of 25-35% of the present level of energy consumption by 1995. The most controversial and progressive feature of the plan is the requirement that residences must be insulated to cost effective levels before they can be resold, starting in 1984, and subject to voter approval of this requirement.

The plan contains 6 major policies, one of which is the retrofit program for the residential sector. This program establishes a "one-stop" conservation center which conducts an aggressive energy conservation marketing program entitled the Energy Savings Center. The center is operated by a private non-profit corporation that acts as a clearinghouse, coordinating information and promoting participation in weatherization services to individuals residing within the city limits.

In a typical Portland home, space heating consumes about 72% of the total energy used, and a reduction in heating requirements of 60% can be achieved if the structure is insulated and weatherproofed. The initial stages of the retrofit program are optional and are accomplished through voluntary participation; mandatory requirements for cost effective* weatherization are scheduled to take effect in 1984, subject to voter approval. However, meeting the weatherization requirements will then be obligatory only at the time a home is sold. The owner will verify to the buyer that an energy audit and the necessary work has been completed.

The city's low interest loans are currently obtainable at 8% interest through a $3 million U. S. Department of Housing and Urban Development Action Grant. These funds are matched locally with $14 million dollars from local lending institutions.

RESEARCH PROGRAMS

Trade association or government sponsored research programs can boost the development of better performing equipment. The National Coal Board in England allocates several hundred thousands of dollars of effort each year toward the development of cleaner burning residential coal-burning appliances. Through the board's Coal Research Establishment, revolutionary conceptual combustion designs are developed and then passed on to private manufacturers (along with funding grants) for commercial production. In fact, on some occasions, the Coal Research Establishment conducts joint research projects with manufacturers of coal burning appliances. **

IMMEDIATE NEED FOR A SIMPLIFIED EMISSIONS TEST AS A MEANS TOWARD ANY SOLUTION

No matter which regulatory or institutional approach is selected to address pollution from residential wood combustion, practically any approach requires a practical test method to measure emission rates. Just as an Olympian is selected by comparing the speed with which he or she can run a race, so must a system of measuring pollutant emissions be used to develop solutions to the wood combustion emissions problem. An Olympian is not selected on the basis of his or her good looks, and when comparisons between athletes are made, all must run the same distance course.

---

* Cost effectiveness standards have been determined to ensure that the cost of weatherization combined with monthly fuel bills is no more than what was previously paid for fuel alone.

** Wood'n Energy, "Coal Burning in the United Kingdom', p. 48., December, 1980.

Experience may indicate that an existing athlete can improve by changing technique or that a new competitor is far superior. But no progress whatsoever towards greater excellence can be made unless there is a standard system for evaluating performance. This view of the importance of performance rating systems can be illustrated graphically as in Figure 1 below. Whether the path towards a solution will rely on education, clean technology research, information distribution, subsidies for cleaner units, or equipment standards, all these programs depend on having a technique for measuring emissions performance at reasonable cost.

The Oregon Department of Environmental Quality is frequently contacted by stove or fireplace designers who want the DEQ to test the emission characteristics of their wood heating unit. Many express interest in paying for emissions testing themselves, but all seem to balk when told that the cost for conducting a single EPA Method 5 test with back-half catch (i.e. including condensible organics) is about $1500. Clearly, an alternative test method is needed that costs on the order of $50 to $100/test or less so that designers and researchers can have rapid and frequent feedback on which design or operation modifications result in fewer emissions.

GOALS IN DEVELOPING A STANDARDIZED EMISSIONS TEST PROCEDURE

There are two different types of test procedures needed to provide useful feedback on wood heating unit emissions performance. Manufacturers and equipment designers need a simple particulate emissions test which produces approximate information on whether a design or operation modification reduces emissions or not. Dozens of manufacturers in Oregon are reluctant to spend approximately $1500 for a single EPA Method 5 particulate emissions test for one test cycle. If a rough measurement technique were available at a cost of $50 to $100, hundreds of stove designers throughout the nation would have an immediate feedback mechanism that would provide information on whether certain modifications improve emissions performance. The development of such a technique could do more toward the development of clean technologies than any other single action.

Secondly, a standardized, more sophisticated emissions measurement technique is needed to enable the fair comparison of emission rates for different units including a method for measuring at similar rates of heat output. Standardizing the emission measurement techniques to be used will not be too difficult a task. Standardizing the method for testing at similar operating rates will be a more difficult process, but this also needs to be done to allow fair comparison between units from different manufacturers. Otherwise test results from a unit burning briskly with an 800 degree stack temperature might indicate that unit is cleaner than one tested at a very slow burn rate and 200 degree stack temperatures, when in fact the latter unit might burn cleaner when similar operating conditions were tested. England's test method for coal burning appliances, electrostatic precipitators, does not effectively capture

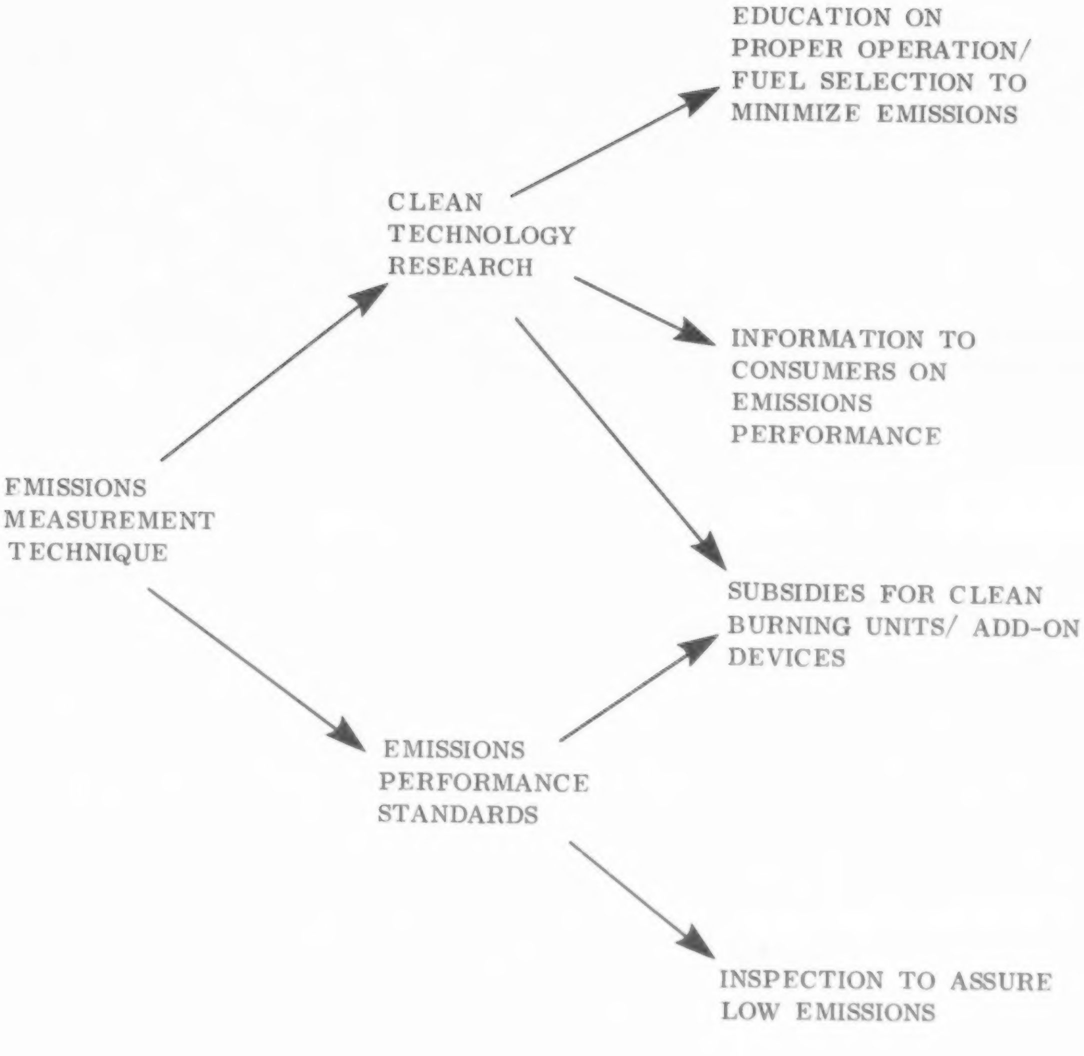

EDUCATION ON PROPER OPERATION/ FUEL SELECTION TO MINIMIZE EMISSIONS
CLEAN TECHNOLOGY RESEARCH
INFORMATION TO CONSUMERS ON EMISSIONS PERFORMANCE
EMISSIONS MEASUREMENT TECHNIQUE
SUBSIDIES FOR CLEAN BURNING UNITS/ ADD-ON DEVICES
EMISSIONS PERFORMANCE STANDARDS
INSPECTION TO ASSURE LOW EMISSIONS

Figure 1. Diagram Showing the Importance of an Emissions Measurement Technique in Developing Almost Any Solution to Residential Wood Burning Air Pollution

condensible organic vapors, but does provide for comparing units on the basis of emissions per 10,000 BTU's of heat output.

Aside from this overview of what the goals are in standardizing emission measurement procedures, the ideal characteristics of a standardized test procedure would include the following:

- Simple test procedure -- a simplified yet useful measurement is needed that would cost considerably less than the $1500 for an EPA Method 5 test with back-half catch, ideally in the $50 to $100 price range.

- Method for standardizing operating procedures -- units cannot be fairly compared with others unless the tests compared are for similar operating procedures and operating rates. Normalizing to similar heat output rates may be useful.

- Reproducibility -- the tests should be relatively reproducable. This probably includes a method for testing with one of several types of standard wood.

- Mobility -- the equipment used should not be so fragile that transport is difficult. A mobile sampling van useable by several designers/manufacturers might provide good economies of scale.

- Condensible organics should be included -- whether a simplified or sophisticated method is being considered, either should indicate the approximate relative amount of condensible organics, since this category of condensible organic emissions represents twice the mass of the solid particulate emissions are.* It may not be necessary to measure this in the simplified method, but the measurement output should be proportional to the amount of condensible organics. Tests with large pore-size filters or elevated filter temperatures (i.e. greater than 150°F) can have poor capture efficiencies for these pollutants.

DISCUSSION OF SOME POTENTIAL EMISSION MEASUREMENT TECHNIQUES

So that some reader may be motivated to develop both a simplified test method and a standardized more sophisticated method, several different possible methods which could be used singly or in combination are briefly discussed below.

Optical Methods

- Visually-rated opacity -- the Ringelmann method or a percent opacity reading can be used to measure the degree of light obscurance by smoke. This method is cheap, simple, and quick, and a smoke observer can become certified as an accurate opacity reader with a two or three day course. Although the density of smoke is generally a reasonable indicator of the approximate mass of smoke in the air, the amount of dilution air can affect the reading as can the temperature at which the plume is observed. Solid particles may cause nucleation of water droplets with a resultant increase (up to a factor of five) in light extinction coefficient. Also light may be absorbed by other materials in the gas phase with a resultant increase in opacity.

---

* Monsanto, Residential Wood Combustion Assessment, DeAngelis & Reznik, 1980.

- Stack transmissometers -- these instruments are used to measure opacity (average light extinction coefficient) of a suspended aerosol, within a stack. Transmissometers can be operated on intermittant or continuous basis and output can be recorded on meter or strip chart.

- Filter Tape Samplers (with optical evaluation) -- For sampling and monitoring airborne particulates and concentrations of smoke. Particulates are collected on a paper tape filter; optical density of the deposit is measured by percent light transmission, reflectance or both. The signal is indicated on a meter or continuously recorded on a strip chart. The meter can map out COH (coefficient of haze) values directly - transmission -(for specific flow rates and sample times i.e., 2 hr., 0.25 cfm, spot samples), or measure RUDS (Reflectance Units of Dirt Shade).

  Depending on model, operation may be manual, semi-automatic or fully automatic for measurement, tape advance and flow adjustments. Reflection or transmission of filter deposits do not measure deposited mass; COH and RUDS values are a measure of optical density as a measure of soiling index. Comparison of optical density with particulate mass *is relative only since the properties of aerosols from wood smoke are non-uniform in their size distribution, composition, and index of refraction. However, changes in filter loadings can be detected with tape samplers. There are tape samplers available for measuring airborne particulate mass with Beta Attenuation devices - which will measure mass accurately.

- Whichever optical method is used, when comparisons are made, some adjustment may be appropriate for excess air and burning rates. Some CO_2 measurement would allow normalization.

---

* There may be a better correlation or relationship between COH and carbon content of particulate matter than between COH and total particulate mass.

Orsat Gas Analyzer -- This apparatus measures flue gas constituents on a percent volume dry basis. CO_2, CO, and O_2 are removed from the stack gases by absorption and excess air can be determined from the orsat readings by stoichiometric calculations.

Firite CO_2 Indicator -- This unit is inexpensive and relatively accurate. CO_2 readings can be used to normalize other measurements for the amount of dilution air. However, as wood volatiles are combusted and the remainder becomes a higher and higher percentage of solid carbon, the ratio of CO_2 produced per pound of fuel decreases.

Continuous CO Monitor -- Since both CO and excess hydrocarbons indicate imperfect combustion, CO measurements might be an indicator of condensible hydrocarbon emissions.

Hydrocarbon Flame Ionization Detector -- Either a continuous or a batch unit (FID-GC) can be used. Organic compounds are converted to carbon atoms and the amount of ionizable carbon measured by the FID. Since only ionizable carbon is measured, some slight innaccuracies can be introduced since carbon atoms in molecules such as CO, urea, and formic acid will not be recorded. A catalytic converter can be used for CO detection. Some CO_2 measurement theoretically could be used to normalize for dilution air. This would allow conversion to an emission factor with units of grams hydrocarbons/grams fuel.

EPA Method 5 -- This method utilizes lo-volume samplers which collect air samples at .75 CFM. A heated filter is followed by a set of impingers. The chief shortcoming of this method is that condensible organics are not efficiently captured by a heated filter and impingers alone. Condensible organics can constitute more than twice as much mass as the other solid particulate matter, per Monsanto in 1979. Another difficulty is that accurate flow measurements are critical. Since sampling flow rates are so low, a considerable length of sampling time is necessary. Accuracy of emission rate measurements are seriously impaired due to the low flow rate.

Oregon Method 7 -- The Oregon Method 7 is the same as EPA Method 5 except that the impingers are followed by a non-heated filter (between impingers 3 and 4) which is presumed to capture considerably more of the condensible organics. Visual observations have indicated for sources such as veneer dryers that more mass can actually be captured by the back-up filter than the front-filter and impingers combined.

Oregon Method 8 -- Oregon Method 8 utilizes a hi-volume sampler with glass fiber filter. Since hi-volume samplers have flows of about 40 CFM, considerably less sampling time is needed to collect a measurable sample than with a lo-volume sampler. However, frequent filter changes are necessary. The sampler can be equipped with a high volume impinger for capture of condensibles.

Total Capture Method -- First referenced by Butcher, in the July 1979 JAPCA Issue, total wood smoke emissions are captured by a single hi-volume sampler. Since total emissions are captured, an emission rate can be determined by dividing the collected emissions by the mass of fuel charged thus avoiding the necessity of measuring the extremely low flows normal to wood stoves. This guarantees integrity of the emission factor calculation procedure, provided the hooding arrangement captures all the emissions. The chief shortcoming of this method is the frequent rate of filter changing needed. With only 1 hi-volume sampler, a filter changing frequency of every 3 minutes may be necessary. If four hi-volume samplers were to be employed, filter changing requirements could be reduced by a factor of four.

This method as first utilized by Butcher, did not provide for any cooling of the hi-volume sampler filter or for any back-up filters. An obvious modification to ensure more complete capture would be to follow the primary heated filter with a set of impingers and a back-up hi-volume sampler with a non-heated filter.

Tracer Gases -- Lo-volume sampling methods such as EPA Method 5 or Oregon Method 7 have potential for simplicity, but the low flow rates in typical wood stove combustion can make accurate flow measurements with conventional Pitot tubes difficult, if not impossible. Introduction of a tracer gas, such as SO_2, at a known rate in the combustion chamber could enable the lo-volume sampler methods to operate with simplicity and better accuracy, since the flow rates could then be precisely determined by measuring the concentration of the tracer after dilution by the stack gas.

CONCLUSION

Residential wood burning emissions have been established to be a significant air pollution problem in Oregon and other areas of the country. In Oregon, 24-hour impacts as high as 82 ug/m^3 have been recorded. In seeking a solution to the problem, a variety of institutional and regulatory mechanisms can be used and have been used. These include 1) performance rating programs 2) programs certifying compliance with standards 3) incentives for equipment replacement 4) inspection programs 5) education programs 6) weatherization programs, and 6) research programs.

The development of any of these approaches, excluding weatherization programs, require the use of some standardized method for measuring emissions, so that all parties involved can receive feedback on which units or operating procedures produce less emissions. If a simplified technique can be developed, a greater number of individuals involved with wood heating device design and operation will have convenient feedback and be able to make more rapid progress toward cleaner burning units.

Numerous existing emission measurement procedures have been discussed in order to provide a foundation for researchers interested in developing a standardized and simplified wood combustion emission measurement technique. Manufacturers and dealers of wood heating devices should team up as other trade associations have to support development of simplified and standardized methods for measuring emission rates and ultimately development of low emission equipment. Only through such a cooperative effort can the best solution to a very serious problem be developed.

WTG:g
AG816.1 (1)

RESIDENTIAL WOOD COMBUSTION ISSUES FOR THE TENNESSEE VALLEY

by: Charles E. Bohac[1]
Joseph R. Duncan[2]
Larry E. Beeman[3]
Tennessee Valley Authority
[1]Chattanooga, Tennessee 37401
[2]Muscle Shoals, Alabama 35660
[3]Norris, Tennessee 37928

ABSTRACT

Impacts on air quality standards, industrial development, human health and safety, and forest resources are the major issues relating to residential wood combustion within the Tennessee Valley.

Although regional particulate levels might not be significantly elevated and regional sulfur emissions could potentially be reduced because of increased wood combustion, residential heating emissions can comprise a high percentage of wintertime particulate emissions for urban areas. Additionally, the chemical content of these emissions can be represented so as to be alarming--dozens of carcinogenic and toxic chemicals contained in small particles that penetrate deep into the respiratory system. Therefore, the local air quality impacts are of a primary concern.

Preliminary estimates indicate that there is ample wood resource available to support even the highest estimates of residential wood heating. However, the combination of all potential demands when considered in the context of accessibility, topography, landowner preference, and the general market-price competition will create many local areas where demand could exceed supply. Additionally, such factors may also create uncertainty in the wood supply and reduce its use for energy below desirable levels.

Other issues addressed include accelerated erosion, nutrient loss, safety hazards to wood harvesters, and fire hazards from improper heater installation and operation.

Alternative means of resolving these issues which are available to local, State, and Federal agencies are also discussed.

INTRODUCTION

Before discussing some of the foreseeable problem issues of residential wood combustion, it is proper to consider some of the advantages that make wood for residential heating important in the Tennessee Valley region. Woody biomass is renewable; its present and long-term potential can be estimated with reasonable accuracy. Wood is domestic, and in the Tennessee Valley region it is relatively abundant and significantly underutilized (Klein, 1979). Increased use of wood for energy would further diversify the region's energy resources. Technology for using wood in residential heating is simple and currently available. An increased demand for wood could lead to more stable and integrated harvesting systems--systems that harvest the forest for a mix of commodities for either the wood industry or the energy consumer, depending upon the current supply/demand and price situation (Doub, 1980). Finally, depending on the scale of production, woody biomass production may provide the basis for the growth of small business enterprises in the rural areas of the Tennessee Valley region.

The exploitation of the wood resource for energy is a controversial issue and one that could become as emotional as surface mining. In discussing this issue perhaps a logical starting point is to admit that: (1) Because of the obvious energy problem faced by this Nation and all its implications, the residential combustion of wood will certainly have a role in helping to resolve this problem; (2) we are not sure what the short-term, much less the long-term, effects will be on the environment, the forest resource base, and regional socio-economics due to significantly increasing use of wood for energy; but (3) we must strive to understand and anticipate these effects because the success of the combustion of wood for energy ultimately depends on the preservation and renewal of the biomass resource, its safety, and the manner in which it impacts the air and water resources of the Valley.

THE FOREST RESOURCE

WOOD AVAILABILITY

The commercial forest in the Tennessee Valley region, which includes parts of seven States, produces a wood equivalent of almost one ton of coal per acre annually (Klein, 1979). Wood use within the Valley region for 1980 has been estimated to be about 2.6 million dry tons/yr. for industrial use and about 1.5 million dry tons/yr. for residential heating (Krickenberger *et al.*, 1980).

It has been estimated that the amount of forest biomass available within the Valley region for increased use above current levels is 25 million dry tons/yr. (Hitchcock, 1980). For comparison, the additional amount of wood used for industrial feedstock, energy, and conversion to liquid fuels for the year 1990 has been estimated to be as much as 13.7 million dry tons/yr. with residential combustion accounting for 10 percent of the increase (Krickenberger *et al.*, 1980).

While the potential is present for significantly increasing the use of wood for energy without competing with conventional uses for wood, there are a number of constraints which could significantly reduce the 25 million dry tons/yr. theoretically available to a much lower figure.

1. Over 87 percent of the commercial forest land in the Tennessee Valley region is privately owned (includes the nine percent owned by forest industries) (Ogden, 1980). Landowner preferences for managing the forest resource significantly limits the available woody biomass for energy.

2. Harvest limitation due to accessibility, topography, and harvest costs.

3. Increased use of logging residues for reconstituted wood products.

4. Economic competition of using other energy sources.

When all the potential demands are compared to the practical estimates of the amount of wood which might be available, these demands could exceed the supply, especially if significant production of liquid fuels from wood is realized. Thus, even though the increased residential demand might be a small component of the total wood-use increase, it could result in a significant impact because the residential demand would concentrate near urban centers rather than being evenly distributed throughout the region.

GENERIC ENVIRONMENTAL ISSUES

Rapidly marketing wood as an energy resource has both positive and negative aspects. One scenario is that a strong demand for wood will provide an incentive for more intensive management that will actually increase forest products with less environmental degradation. Another likely scenario is that shortsightedness and destructive exploitation will prevail. Which scenario unfolds will depend on how landowners, the forest product industry, small logging operators, State and Federal regulatory agencies, and other groups affecting forest management practices respond to an increased demand for wood as an energy resource. Nevertheless, it is possible to identify problem areas that are likely to be encountered (Office of Technology Assessment, 1980).

The degree to which residential wood heating will contribute to these problems in relation to the problems caused by other wood demands is not yet well known. Therefore, discussing the forest resource issues generically perhaps unfairly biases one's perception of the problems associated with wood heaters. It is hoped, however, that the issues discussed are those which pertain, as much as possible, to residential wood heating.

There will be an increased incentive to harvest marginal lands that have severe management constraints such as steep slopes, erodible or thin soils, and nutrient deficiencies. Harvesting timber on these lands has significant environmental implications because of the high risk of soil erosion and nutrient depletion and the ultimate reduction in productivity. While marginal lands have limited value for commercial forest production, they do have value for watershed protection, esthetics, recreation, and wildlife habitat.

Greater removal of biomass combined with shorter rotation cycles have raised suspicions that nutrients and organic matter will be removed from the soil to the extent that forest productivity will decline (McCarthy, 1979). Adding fertilizers is not necessarily a viable solution to this problem since it will not only add to costs but reduces the net energy gain in using wood for energy. This issue is further complicated because the solution is likely to be extremely site specific, thus eliminating development of any general management techniques.

Since almost 80 percent of the commercial forests in the Tennessee Valley region are owned by private, nonindustry individual landowners and is frequently in small land tracts, much of the harvesting is done by individuals inexperienced in logging and silviculture (Ogden, 1980). This is especially true for increased wood use in residential heating. Damage to the forest resource due to improper logging techniques from these small-scale harvest operations will likely accelerate, especially with growth in the use of residential wood stoves.

Although significant high-quality forest land is available in the Tennessee Valley region, local variations of poor management practices may expose vulnerable lands to exploitation. The long turnover rate to recoup the benefits of good forest management as well as the tendency for some benefits (such as prevention of water quality degradation) to accrue to adjacent landowners and the public rather than to the landowner himself limits management incentives. This is anticipated to be especially true in the fuel wood industry where because of relatively low capital investment there may be a greater tendency to "cut and run" than when wood is harvested for large capital-intensive industries like pulp and paper which must ensure a future timber supply to protect its significant capital investment.

RESOLUTION OF FOREST RESOURCE ISSUES

The resolution of the forest resource related issues within the Tennessee Valley region will be approached by first working with landowners through a number of technical assistance programs of State and Federal agencies. TVA has developed several typical programs.

The first program, called the Consulting Forester Program, helps new consulting foresters become established in a geographical area by supplementing their income during the first years of their practice. Services offered by the foresters include forest management, forest inventory, appraisals, sales preparation and administration, damage and litigation representation, and nearly all forest resource related work.

By organizing private forest owners through the Consulting Forester Program, TVA believes that it will: (1) Help to ensure efficient and environmentally sound harvest techniques of otherwise unmarketable wood; (2) help ensure fair market compensation to the small forest owners; and (3) improve the management of small forest stands (Doub, 1980). In addition, it will aid the reliability of the woody biomass at local levels and help encourage investments in wood energy conversion equipment.

One of the primary reasons private landowners do not implement forest management for energy production is that they are interested primarily in the many other benefits that forests provide. These other benefits include wildlife, recreation, soil protection, and aesthetics. Because of these landowner interests, TVA has developed the Woodland Resource Analysis Program, which attempts to capture the interest of small landowners by preparing for them a tailored plan for optimizing a mix of benefits. In other words, production of wood is managed in such a way to meet the land management goals of the landowner and yet encourage the use of wood for conventional forest products and energy.

The development of an effective fuel-wood marketing system is needed to establish reliable an economic supplies of wood energy. Only through established systems can the cost of wood biomass be competitive and supply to consumers be made dependable. It is hoped that such a system would also help to relieve fuel-wood pressure around urban areas. TVA has recently established two fuel-wood yards in order to study their effectiveness.

Finally, it must be realized that there is a great deal of uncertainty in promoting wood for energy. Serious environmental damage may result if the wood supplier does not manage the resource properly, including site selection, harvesting, and reestablishing forest productivity according to environmental guidelines. For this reason, TVA is taking steps to continuously inventory the forest resource base and monitor the effects of increased use of woody biomass for energy. In cooperation with the Forest Service, TVA is designing an inventory system that will allow an evaluation of the impact on the forest resource.

The inventory information must be used as feedback to the decision-making process so that Congress and the State governments can see the results of their incentives to promote all uses of wood for energy. Only in this way can adequate policy options be developed and maintained. The forest resource inventory is also essential to residential heating by allowing major industrial development, such as the pulp and paper and alcohol fuels industry, to select plant sites and procurement areas which will be compatible with residential fuel wood procurement. It will also be important so that these industries can curtail procurement in areas where over-cutting is projected. The information will also be important to agencies responsible for technical assistance programs aimed at promoting sound management practices in order to determine if these programs are sufficient or if regulations such as requiring permits for all wood harvesting in particular areas are needed. In short, a continuing inventory process, especially if augmented with soil nutrient monitoring, will be essential to periodical review of policies which, of necessity, are presently being made in the face of significant uncertainty.

SAFETY

WOOD COMBUSTION

Because of the increased potential for fire related to wood heater use, TVA has initiated a safety technical assistance and inspection program as a part of its wood heater program. TVA's role to promote the safe use of wood heaters includes requiring stoves approved for installation in the TVA program to meet minimum safety requirements and that they be installed properly. In addition to inspecting the installation of each heater installed as part of the TVA program, TVA makes available to anyone who asks detailed instructions for the installation of equipment, including proper chimneys to be used and clearances to combustible surfaces. The consumer is also supplied with other information concerning potential hazards involved with the use of equipment, including the use of flammable liquids, the potential burns from the hot surfaces of the stoves, and possible consequences resulting from overfueling (TVA, 1979).

One of the most effective parts of TVA's wood heater safety program is the training provided to wood heater installers, local fire chiefs, and code inspectors. Although trained primarily for the TVA program, the trained installers increase the likelihood of safe installations throughout the Valley, whether or not the heater is part of the TVA program.

WOOD HARVESTING

Presently, the accident rates per worker for forest biomass harvesting are approximately twice those for bituminous coal mining. If safer logging practices are not developed, safety could become a part of labor management relations similar to the issue safety has played in the mining industry. This could lead to an increase in the potential for strike-related supply interruption (Office of Technology Assessment, 1980). Harvesting safety will be an especially important issue on small tracts of land where harvesting is done by individuals inexperienced in logging. To these ends, it is believed that forest management technical assistance programs should also emphasize safe harvesting practices, especially when working with small private landowners or the infant fuel wood procurement industry.

AIR QUALITY

OVERVIEW

There is a significant potential for air quality degradation by residential wood burning, and the situation may be overtaking us. About 190,000 or 9 percent of the homes in the Valley region used wood as their primary fuel for heating in 1976. A recently completed residential survey indicates that 13.7 percent or 315,000 homes in the region used wood for heating in 1979 (TVA, 1980).

The survey results confirm that many Valley residents need little encouragement to burn wood in some way and as a result, several air quality issues are surfacing: (1) The impact upon ambient air quality, (2) the impact upon health, (3) the impact upon economic development, and (4) the impact upon the ability of State and local agencies to achieve regulatory plan objectives. A brief summary of each of these follows.

IMPACT UPON AMBIENT AIR QUALITY

Several efforts have been made within the Valley to determine the potential ambient air quality impact from residential wood heaters. An area source approximation method was used to estimate the local ambient impact for individual wood-heating units (low density) and for 1000 units per square mile (high density) (Duncan et al., 1980). The results of this approximation for five of the seven criteria pollutants for which there are ambient air quality standards indicate that the standards which would be impacted most significantly are the 24-hour particulate standard (260 $\mu g/m^3$), the 8-hour carbon monoxide standard (10,000 $\mu g/m^3$), and the 3-hour hydrocarbon standard (160 $\mu g/m^3$). A field study is being conducted during the 1980-81 heating season by TVA for the purpose of quantifying the local ambient concentration of pollutants due to residential wood burning.

A regional air quality assessment of increased wood burning has also been performed. The study evaluated the regional air quality impact for 25 and 50 percent residential penetration of wood heaters in the region. Results show that if 25 percent of the Valley's residents heat with wood, the 24-hour maximum total suspended particulate concentration could increase by 4 to 5 $\mu g/m^3$ over the region and to 10 $\mu g/m^3$ for a 50 percent penetration (Tong et al., 1979). These predicted pollutant increases from wood heating are put into perspective by comparison with "maximum allowable increases" of 10 $\mu g/m^3$ for Class I and 37 $\mu g/m^3$ for Class II areas as provided by Prevention of Significant Deterioration regulations. Concentrations on a local scale could be much higher than the regional levels, however. TVA is conducting a winter heating study jointly with EPA and DOE to quantify the local impacts.

IMPACT ON HEALTH

In addition to the implications for adverse health effects when ambient air quality standards are exceeded, other noncriteria chemical constituents of wood burning emissions may be of still greater concern. These chemical constituents have generally been detected in the particulate fraction of the emissions from residential wood heaters, and these particulates are reported to comprise 20 to 40 percent of the total particulate levels in some communities during the winter heating season (Cooper, 1980). Studies (Snowden et al., 1975; EPA, 1980; DeAngelis et al., 1980; Cooper et al., 1980) undertaken in recent years in an attempt to quantify various components emitted from wood combustion have identified about 100 compounds in the combustion products. These emissions are of primary concern insofar as health implications because:

1. Many emitted constituents are known carcinogens and mutagens in laboratory animals and strongly suspected to be carcinogenic in humans.

2. Since these emissions are released into the ambient atmosphere at ground level or inside residences, the potential for immediate human exposure is much greater than if emitted through industrial stacks.

3. 50 to 75 percent of the particulate emissions are in the inhalable range.

Many heater manufacturers are advertising wood heaters "as capable of burning wood or coal." This is cause for concern because although little coal emission data exist for stoves being marketed today, the available data indicate from 2 to 20 times more carcinogenic material and sulfur dioxide are emitted during residential coal burning than during wood burning. Thus it will be important to ensure an adequate wood supply once heaters become established in order to keep them from shifting to coal.

Adverse health effects caused by buildup of indoor air pollution from residential wood burning have not yet been quantified. However, with the trend to "tighten" homes by increased insulation and improved weatherization, indoor levels of pollutants will be increased and wood combustion could add to the problem. Additionally, exposures are likely to be high during the heating season because more time is generally spent inside the home during winter.

The indoor air quality problem raises some interesting issues in relation to the concern for ambient air quality. For example, indoor air respirable suspended particulate levels can routinely exceed 200 $\mu g/m^3$ when smokers are present (Repace and Lowery, 1980). Because indoor levels might in some cases well exceed ambient standards, they might argue against the case for stringent ambient standards. However, before ambient standards are dismissed too quickly, it must be understood that indoor background levels come from outdoors, there are definite cause and effect relationships between emissions and illness, and that if peak exposures determine health effects, even spending a short time outside in the presence of high concentrations could be harmful (Budiansky, 1980).

IMPACT UPON ECONOMIC DEVELOPMENT

The potential magnitude of residential heating emissions is illustrated with the case of Chattanooga. If 20 percent of the residences in Chattanooga were to heat with wood or coal, the resulting rate of particulate emissions during the heating season would be equivalent to existing industrial sources (about 4000 tons/year). The carbon monoxide emission rate would be equivalent to 60 percent of all sources within Chattanooga, including transportation and industrial sources (about 75,000 tons/year).

Because the five major Valley urban areas do not presently meet ambient air quality standards for particulates or carbon monoxide, residential space heating will complicate the attainment of these ambient standards. Industries might also be required to offset any additional emissions in these areas, especially if new industries are to locate in Valley urban areas. Because of the potential level of residential emissions to be offset, residential space heating could have a limiting effect on industrial development if significant additional penetrations of wood and coal heating takes place.

An advantage of wood heating is that if 40 percent of the residences in the Valley presently heating with electricity convert to wood heating, TVA sulfur emissions could be reduced by 3 percent. In terms of the costs of TVA's commitment to reduce sulfur emissions by 40 percent, this equates to a value of about $100 million in sulfur oxides control. But this benefit would be traded for perhaps other costs in particulate and carbon monoxide air quality losses, using the wood stoves now being marketed.

It is hoped that wood heaters can be significantly improved from the standpoint of emissions. Through an extensive testing program conducted by TVA, it has become apparent that even within the present generation of wood heaters, that a several-fold difference in emissions exist. This illustrates the potential that improvements in wood heater design can mean in terms of lower emissions (Harper, 1981).

Aside from the hoped-for "nonpolluting" residential wood heaters of the future, it is safe to say that in the short-run at least, the use of wood for energy without significant local air quality impacts will be achieved only through large units where process and control equipment costs can be accommodated. These "large units" can employ direct combustion, pyrolysis, or gasification. However, the economics favor use of wood wastes for such units; harvesting and transporting a high-moisture, low Btu/lb fuel poses a serious economic barrier.

IMPACT UPON STATE AND LOCAL PROGRAM OBJECTIVES

Nationally, air quality regulations have concentrated mostly on large industrial emission sources, but State Implementation Plans have from the outset addressed a full range of sources. Many State and local authorities have used such methods as banning open burning and restricting the use of hand-fired combustion units to fight growing air pollution problems.

In the predominantly rural Tennessee Valley the use of solid fuel in industrial combustion units is the traditional source of process steam and heat. Some restrictions were placed on these type sources in the early 1900's in the urban areas where visible smoke presented the greatest problem. However, as has been the case with other traditionally accepted activities, the States have had neither the resources nor the political influence to impose restrictions in a rural setting.

Although emissions from residential heating were a concern in the Valley into the 1950's, continued electrification and the increased availability of natural gas and propane for residential heating negated the need for restrictions on residential combustion sources during the 1960's and 1970's. Even in the modern generation of State regulations promulgated subsequent to the Clean Air Act of 1970, the need for restrictions on residential units was not apparent, and the difficulty in regulating these sources led to their specific exclusion.

In recent years the rapidly escalating price of clean gaseous and liquid fuels has led to renewed interest in solid fuels as an economical alternative. It is now becoming apparent that if the present trend is not checked, significant ambient impacts may result. This projection combined with the continually increasing volume of data concerning the potential health effects of wood-burning emissions has focused regulatory attention on the issue. Restrictions on wood burning for residential space heating have already been imposed in certain areas around the country and it seems likely that restrictions will be necessary in other areas, perhaps including the Tennessee Valley region. If, in fact, the present trends continue unchecked, Federal restrictions may be imposed. This could lead to the imposition of unit emission limitations on the manufacturer as has been the case in the automobile industry.

In contrast to the limited regulatory activity in the area of residential combustion, commercial and industrial combustion of solid fuels including biomass has been the subject of State regulations since the promulgation of regulations under the Clean Air Act of 1970. In most States sources as small as 1 to 2 million Btu's per hour have restrictions on the emissions to the atmosphere. For example, the States of Alabama and Tennessee have specific regulations for wood-fired, fuel-burning equipment. These regulations reduce emissions by a factor of 10 when compared to the residential wood heater particulate emission rates from the best heaters under optimum conditions, and could reduce them by as much as 100 times when compared to wood heaters under starved-air operating conditions.

RESOLUTION OF AIR QUALITY ISSUES

If it is ultimately determined that emissions from residential heating do adversely impact air quality standards in some Valley areas, regulations banning or restricting their use could follow. This becomes more probable in the larger urban areas of the Valley which might lose industrial development and where precedents for the restriction of residential heating already exist.

Although the health risk posed by residential wood heating clearly exceeds that of gas heat and probably exceeds that associated with electric heat from coal generation, its resolution remains obscure at least until better quantification is made of several factors. These factors include indoor air pollution and the proportion of total personal exposure for which wood heaters are responsible. If additional regulations are to follow, they may take the form of emission limitations which would require the manufacture of less polluting wood heaters or possibly building code revisions to require more air changes per hour if indoor pollution is found to be the controlling factor.

In whatever way the wood heater air quality problems are resolved in the future, the development of less polluting units is to be encouraged now.

SUMMARY

Wood energy must be developed in order to provide an additional energy option to the Tennessee Valley region. This development must occur in partnership with the forest products industry, the private forest landowners, and in harmony with the Valley's air quality and other natural resource factors. It is apparent that the issues are complex and a great deal of uncertainty currently exists concerning their resolution. It is therefore extremely important to maintain flexibility in establishing policies that promote wood for energy and to continue investigative efforts in order that those policies can be periodically reevaluated in light of new and better information. Finally, even though many of the forest resource and air quality issues might not be resolved for some time, the institution of safety assistance programs, inspections, and code changes can be effective immediately in reducing death, injury, and property loss.

REFERENCES

1. Budiansky, S., 1980, "Indoor Air Pollution," Environmental Science and Technology, 14, 9.

2. Cooper, J. A., 1980, "Environmental Impact of Residential Wood Combustion Emissions and Its Implications," Oregon Graduate Center.

3. Cooper, John A., et al., 1980, "Impact of Residential Wood Combustion on Urban Air Quality: First Ambient Measurements," Preprint, 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, Canada, June 22-27.

4. DeAngelis, D. G., et al., 1980. "Source Assessment: Residential Combustion of Wood," Monsanto Research Corporation for EPA, Research Triangle Park, North Carolina.

5. Doub, R. L., 1980, "Wood Energy--Is it New Competition for the Hardwood Resource," Proceedings of John S. Wright Forestry Conference, "Opportunities and Constraints in Utilization of the Hardwood Resource," Purdue University, West Lafayette, Indiana.

6. Duncan, R., et al., 1980, "Air Quality Impact Potential From Residential Wood-Burning Stoves," 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, Canada, June 22-27.

7. Environmental Protection Agency, 1980, "Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment," EPA 600/7-80-040, U.S. EPA, Research Triangle Park, North Carolina, March.

8. Hitchcock, H. C. III, 1980, "Provisional Forest Biomass Statistics for the 201-County Tennessee Valley Region," TVA, Division of Land and Forest Resources, Norris, Tennessee, Technical Note B38.

TYPING GUIDE SHEET

9. Klein, L. E., 1979, "Wood-Stove Role as an Alternative Fuel," TVA, Division of Land and Forest Resources, Norris, Tennessee.

10. Krickenberger, K. *et al.*, 1980, "TVA's Wood-for-Energy Program Integrated Environmental Assessment," MITRE Corp., McLean, Virginia.

11. McCarthy, D. A., 1979, "The Potential Environmental Impact of Harvesting Wood for Energy," TVA, Division of Land and Forest Resources, Norris, Tennessee.

12. Office of Technology Assessment, 1980, "Energy from Biological Processes. Superintendent of Documents," U.S. Government Printing Office, Washington, DC, Catalog Card Number 80-600118.

13. Ogden, W. H., 1980, Personal Communication, TVA, Division of Land and Forest Resources, Norris, Tennessee.

14. Repace, J. L. and A. H. Lowery, 1980, "Indoor Air Pollution, Tobacco Smoke, and Public Health," *Science*, 208, May.

15. Snowden, W. D. *et al.*, 1975, "Source Sampling Residential Fireplaces for Emission Factor Development," EPA 450/3-76-010, U.S. EPA, Research Triangle Park, North Carolina, November.

16. Tong, E. Y. *et al.*, 1979, "Regional Air Quality Assessment for the Tennessee Valley Authority: Air Quality Assessment of Increased Wood Burning," Teknekron Research, Inc., Boston, Massachusetts.

17. TVA, 1979, "Inspection Checklist for Airtight, Freestanding Wood-Burning Heating," Solar Applications Branch, Division of Energy Conservation and Rates, Chattanooga, Tennessee.

18. TVA, 1980, "1979 Residential Survey - Customers of Local Electric Systems Distributing TVA Power," Internal Report, Analysis Staff, Division of Energy Use and Distributor Relations, Chattanooga, Tennessee, November 1980.

TYPING GUIDE SHEET

WOOD ENERGY - THE NORTH CAROLINA EFFORT

by: (Ms) Phyllis Brooks Wainwright, P.E.
Project Manager - North Carolina POM Study
Division of Environmental Management
North Carolina Department of Natural Resources
and Community Development
P. O. Box 27687
Raleigh, North Carolina 27611

ABSTRACT

The State of North Carolina is committed to wood as an alternative energy source and at the same time recognizes its responsibility to the environment. Because of conflicting Polycyclic Organic Material (POM) emission data available the State of North Carolina has undertaken a sampling study for POM emissions from wood fired boilers. The North Carolina wood energy project and the POM sampling study will be discussed.

WOOD ENERGY - THE NORTH CAROLINA EFFORT

INTRODUCTION

North Carolina has historically been a tree growing State. Today, North Carolina is still heavily forested. Of its 30 million acres, approximately 20 million are in forests.(1) Most of these forest lands have been harvested two and three times since the turn of the century and; today however, much of these forested lands are covered with low quality trees which are not usable for saw timber.(1) Due to limited markets for reconstituted wood products such as paper, fibreboard, etc., much of this material has little or no market value in North Carolina.

A recent analysis of a 1974 forest resource inventory of North Carolina forests, conducted by the U.S. Forest Service in cooperation with the N.C. Division of Forest Resources, estimates that of 31.5 million tons of low quality wood potentially available annually, only 14.6 M tons/yr are commercially available because of terrain, access, and transportation.(1) Should this 14.6 million tons be used by industry as fuel to replace current oil consumption, it would reduce North Carolina's oil consumption by approximately 20 million barrels per year or 24% of the gross yearly industrial energy needs for North Carolina.(11) Twenty million barrels of oil, incidentally, would fill 32,308 railroad tank cars, a train 385 miles long.

TYPING GUIDE SHEET

Recognizing this potential and the need to develop alternative energy sources, Governor James B. Hunt, Jr. of North Carolina authorized the formation of a wood energy coordinating group in late 1977. The purpose of this group is to coordinate programs of participating agencies so as to effectively promote and develop wood for energy.(2) The coordinating group is composed of five members from State agencies involved with wood energy and the State University system. In December 1978 a plan to promote the use of wood for energy was adopted.(3) This plan called for developing wood energy use in non-forest product related industries. At about this same time the group recognized the need for additional expertise in several areas, including the environment, and formed committees for each of the areas of concern. The Air Quality Technical Committee was given the responsibility to review the various activities of the coordinating group, assess the environmental concerns and offer recommendations and opinions. The Air Quality Technical Committee membership is made up of state and federal environmental engineers, a private consultant, and representatives from private industry. One of our industrial representatives boasts of having the largest wood-fired boiler in the State, and another of being the State's largest residential wood stove manufacturer. The consultant is not only an expert in wood boiler design but also an inventor and has several patents pending on devices for wood fired systems. The membership of this committee is a good cross section of regulatory and industry people, and recommendations and opinions from this group reflect various schools of thought.

STATUS OF WOOD FUEL USAGE

One of the first items on the Air Quality Technical Committee agenda was to review the status and associated problems of wood fuel usage in N.C. Because of the tremendous consumer interest in residential wood stoves, as well as the unfavorable emissions reports for wood combustion from EPA, it was necessary that the committee assess these factors in light of the North Carolina wood energy program.

Residential wood stove manufacturers in the State of North Carolina report sales of 125,000 airtight wood stoves within the State since the beginning of the present boom in 1976, with 50,000 of that figure having been sold just this past year.(5) It is estimated that prior to 1976, there were 65,000 existing wood stoves in the State.(6)(9) It has been reported that in 1976 the fuel usage was 3.5 cords per stove.(6)(9) If we assume this same fuel usage per stove today, North Carolina residents are consuming 665,000 cords of wood this winter or enough wood to build a 4 foot x 4 foot pile a thousand miles long.

ENVIRONMENTAL EFFECTS

How does fuel usage of this magnitude affect our environment? Emissions from air tight wood stoves are:

TYPING GUIDE SHEET

Particulate (7)	15,000 tons
CO (4)*	370,000 tons
POM (4)	190 tons

These emissions would fill 5136 railroad hopper cars** - a train over 45 miles long.

Emissions from fireplaces are considerably less than those of wood stoves. If the same 665,000 cords of wood burned in this State this winter were consumed only in fireplaces, emissions would be:

Particulate (7)	10,000 tons
CO (4)	30,000 tons
POM (4)	25 tons

These emissions would fill 534 railroad hopper cars** - a train only about 5 miles long.

Consumption of 665,000 cords in industrial boilers would produce the following emissions:

Particulate (7)	3,000*** tons
CO (4)	1,000 tons
POM	Unknown

In this case, the emissions loaded train will only have 53 cars and would be less than 0.5 miles long. Table 1 compares these emissions.

	Industrial Wood fired boiler (Tons)	Fireplace (Tons)	Airtight Nonbaffled Wood stove (Tons)
Particulate (7)	3,000***	10,000	15,000
CO (4)	1,000	30,000	370,000
POM (4)	Unknown****	25	190

Table 1. Annual Emissions from Burning 665,000 Cords of Wood

From the annual emissions figures in Table 1, it can be seen that the total emissions from the residential wood stove are almost 100 times greater than those from the controlled industrial wood-fired boiler. It should be kept in mind that these are annual emissions and that wood stoves are used only during the winter months. In order to properly compare the impact from residential stoves to industrial wood boilers, they should be examined for the same time frame. Assuming a 4 month winter heating season, it would take 14,400 wood-fired industrial boilers, producing 30,000 pounds of steam per hour, fired 24 hours a day, 7 days a week, for 4 months to equal the total impact from our 190,000 residential wood stoves.

---

* Assuming nonbaffled stoves

** By weight not volume

*** Controlled emissions 60% efficiency

**** No POM emission factor available

Is the promotion of industrial wood energy a sound environmental policy? One aspect of this question is unanswerable at this time; i.e., what are the polycyclic organic material (POM) emissions from an industrial wood-fired boiler? Available industrial (POM) data is currently limited and conflicting. The Air Quality Technical Committee was concerned because of the highly carcinogenic properties of some of the POM compounds found in these emissions.(8) In December 1980 the Committee recommended to the Wood Energy Coordinating Group that the State of North Carolina take the initiative and develop the missing POM data. The North Carolina Division of Environmental Management agreed to sample for POM emissions from industrial wood combustion. A program has been established and funding obtained from the U.S. Environmental Protection Agency as well as from the North Carolina Energy Institute to sample 8 industrial wood-fired boilers for POM emissions. The objective is to determine the POM emission level in well designed and properly fired wood fuel boilers and to determine whether these emissions vary with a change in the fuel moisture content. The State will sample three dry* wood fuel boilers, three wet** wood fuel boilers, and one boiler burning dry* wood on one test and wet** on the next test. Testing will be conducted using a modified Method 5 sampling train.

This testing program is just getting under way, therefore, no results are available at this time. However, it is felt that the testing results will show that POM emission levels from wood, when burned industrially in well designed and properly fired boilers, are no higher than those from coal.(10) It is possible that POM emissions are even less than those from coal. Preliminary results will be available in June and the final report by September.

CONCLUSIONS

What will these testing results tell us? They will give us a number for industrial wood combustion that can be referenced against other fuels burned but, whatever the number, it will not tell us if the POM emission is dangerous to public health and welfare. As of this time no safety limit has been established by the EPA for POM emissions, and until this is done, we have just a number. It can be argued that any emission that is carcinogenic is dangerous; however, the world is covered with carcinogenic matter of one kind or another in varying quantities. If we are to run away from everything that is carcinogenic, we would be living within a protective bubble for the rest of our lives. Realistic safe limits, recognizing some acceptable level of risk, will have to be assigned to POM emissions by the EPA.

Several urban areas of North Carolina are currently recording CO readings in excess of the primary standards during the winter months. Until recently residential wood stoves have not been considered as significant CO sources; however, from the recently published emissions data for wood stoves (4,8,9) it can be shown they can no longer be considered insignificant CO sources in our urban areas. Future CO models in our urban areas will likely include emissions from residential wood stoves and fireplaces. These emissions can no longer be ignored.

Because of the intense interest within North Carolina to burn wood as a fuel both industrially and residentially, the Air Quality Technical Committee will present these facts and concerns to the Air Quality Advisory Council of the North Carolina Environmental Management Commission at their February 1981 meeting. It is not known what action the council will take regarding CO emissions from residential wood stoves; however, any action on POM emissions will probably be taken after the industrial testing results are available in September.

REFERENCES

1. Deal, Earl and H. J. Green *Report of the Resource and Harvesting Committee of the North Carolina Wood Energy Coordinating Group*.

2. Memorandum of Understanding, Wood Energy Coordinating Group, James B. Hunt, Governor of North Carolina, September 21, 1977.

3. *A Plan to Promote the Use of Wood for Energy in North Carolina, A Working Document of the Wood Energy Coordinating Group*. Adopted December 14, 1978.

4. The Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency *Conventional Combustion Environmental Assessment* August 1980.

5. "Situation Report from the N.C. Air Quality Technical Committee of the Wood Energy Coordination Group." December 1980.

6. Duncan, Workin and Schmierbach, *Air Quality Impact Potential from Residential Wood-Burning Stoves* Tennessee Valley Authority, Muscle Shoals, Alabama, 1980.

7. U.S. Environmental Protection Agency *Compilation of Air Pollutant Emission Factors* (AP-42 with Supplements 1-9).

8. De Angelis, Ruffin, Peters and Reznick *Source Assessment: Residential Combustion of Wood* Monsanto Research Corp, March 1980. (EPA-600/2-80-0426)

9. De Angelis, Ruffin and Reznick *Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment* Monsanto Research Corporation, March 1980. (EPA-600/7-80-040)

10. Meuser, Cooke and Smithson *PAH Analysis for Industrial Wood/Bark Boiler Samples* Battelle Columbus Laboratories, April 1980.

11. U.S. Department of Energy *State Energy Data Report*, April 1980.

TYPING GUIDE SHEET

PRELIMINARY ANALYSIS OF THE AMBIENT IMPACTS OF RESIDENTIAL WOODBURNING IN WATERBURY, VERMONT

by: Cedric R. Sanborn
Richard L. Poirot
Gregory A. Heil
Michael A. Blanchet
Agency of Environmental Conservation
Department of Water Resources and
Environmental Engineering
State Office Building
Montpelier, Vermont 05602

INTRODUCTION

During the winter of 1979/80, the Agency of Environmental Conservation conducted an ambient air monitoring program in Waterbury, Vermont to study the effects of residential woodburning on particulate levels within the Village. Prior to setting up the ambient monitoring program, a door-to-door survey was conducted in the Village to determine the number of wood users and their location. The siting of the hi-volume samplers was based on this information.

In all five sampling sites for the measurement of Total Suspended Particulates (TSP) were set up. The data collected at these sampling sites and a meteorological station was used in conjunction with modeling and regression techniques to predict the contribution of woodburning to the TSP levels in Waterbury. Based on these techniques, it was estimated that up to 35% of the measured TSP could be due to residential woodburning.

PARTICULATE SAMPLING SITES

The purpose of the monitoring network was to measure microscale TSP impacts of woodburning on residential areas. The site locations were selected based on the wood use survey for Waterbury and represented conditions where it was felt that woodburning impacts would be the highest. Total Suspended Particulates (TSP) data was collected at five locations in the Village of Waterbury. Three of the sites (Eldredge, Deal and Pool) were located in residential areas. The fourth site was located approximately 1.5 miles north of the Village at the treatment plant and served as a background site. The fifth site, at Osgood, which is located at the State Hospital, was an existing site, and due to its height (approximately 40 feet) acted as a background site. Figure 1 shows the location of the five sites in relation to the Village. Each site contained two hi-volume samplers. At all of the sites except Osgood, one sampler operated for a twenty-four hour period (midnight to midnight) and the other from 3 a.m. to 9 a.m. The purpose of the six hour sample was to measure the particulate concentration at a time when inversion conditions were most likely to occur. Both of the samplers at the Osgood site operated for a 24-hour period with the second sampler used for quality assurance purposes. Samples were collected on a three day schedule from the end of December 1979 to April 6, 1980.

The Eldredge site also contained a carbon monoxide analyzer and an ambient particulate monitor (APM) for outputting hourly total and respirable particulate levels. Additionally, a meteorological station was established adjacent to the Vermont State Hospital.

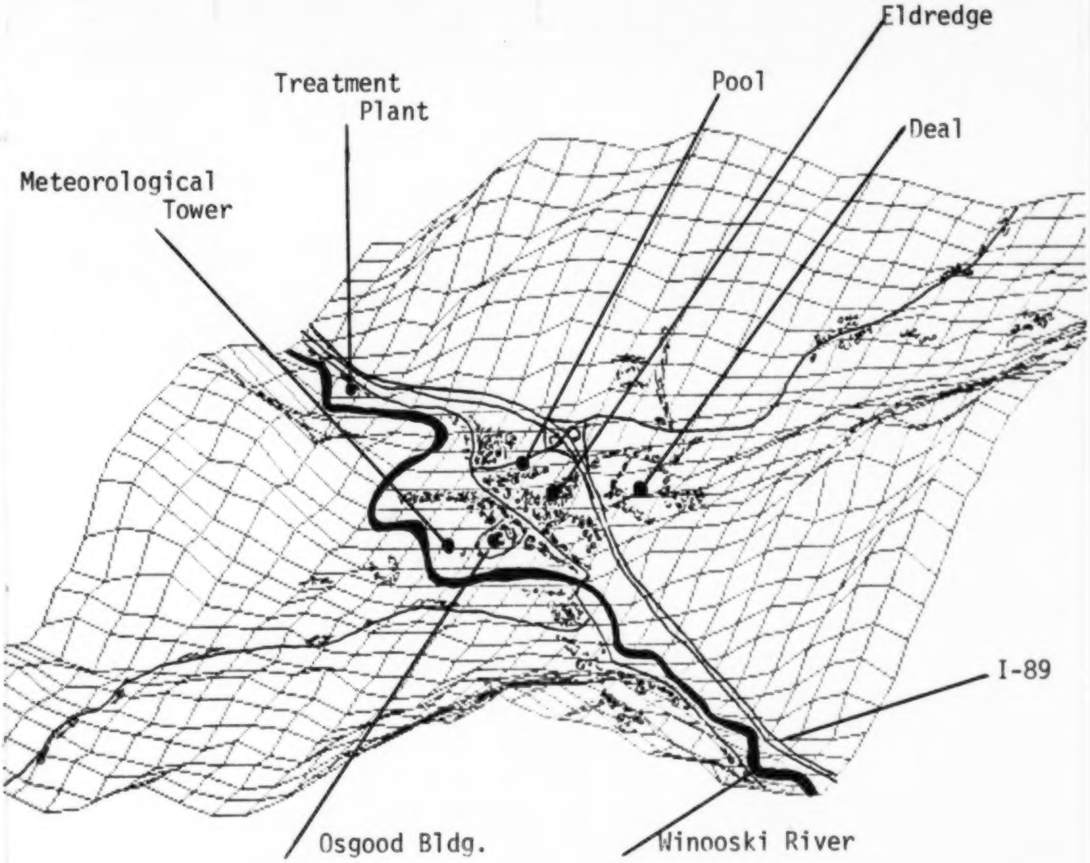


Figure 1. Location of Sampling Sites

TSP LEVELS - 24 HOUR

Excursions of both the primary and secondary NAAQS for TSP were recorded at the Deal site. This site was located in position to record the maximum impact of residential woodburning and did not meet EPA requirements for siting. The sampler was two (2) meters above the ground and four (4) meters away from a paved road. A single violation of 158 ug/M^3 was also recorded at the Eldredge site, which also did not meet EPA siting requirements. All of the excursions occurred in late March and early April during a time when there was no snow cover, and ambient temperatures had warmed up. On the days that the violation occurred woodburning in the Village would be expected to be minimal.

The average TSP concentrations reported at the Treatment Plant (39.3 ug/M^3) and the concentration at Osgood (36.2 ug/M^3) are statistically equivalent. The Treatment Plant was the designated background site, while Osgood is a downtown site that is operated year round and appears to be acting as a background site. The Treatment Plant site was located two (2) meters off the ground while the Osgood site is approximately 12 meters above ground level. Additional comparison testing showed that the TSP levels measured at Osgood do not differ significantly from season to season. Additional filter analysis is being conducted to determine the composition of the material on the filters collected at both sites to see if there is a variation in the material collected. This additional analysis will help to determine whether or not wood smoke emissions remain localized.

The remaining three sites (Eldredge, Deal and Pool) had average 24-hour concentrations of 77, 81 and 62 ug/M^3 respectively. No TSP violations of NAAQS were recorded at the Pool site.

TSP levels at the monitors may also have been influenced by the open winter, which resulted in mild temperatures and relatively little snow cover. The warm weather most likely resulted in less wood burnt and a decrease in the intensity of inversions (although the number of inversions may have remained the same). The lack of snow cover, allowed an excessive amount of dust to blow around. Sampling sites that are set up in residential areas to measure the maximum impact of woodburning at the breathing level, may also be unduly influenced by ground level emissions of dust, etc.

The microscale approach of measuring TSP levels, represents levels that the people in the area are subject to. This approach does not in any way attempt to represent the total picture for the Village. A microscale analysis becomes extremely important if woodburning emissions impact close to the ground (as is common) and/or remain localized.

WATERBURY EMISSION INVENTORIES

Previous experience in producing inventories for other Vermont towns and municipalities indicated that area source emissions in this state are generally dominated by entrained dust from paved and unpaved roads, motor vehicle exhaust and residential wood smoke (99% of total 1980 area source emissions in Barre, 97% in Burlington). Because of this, inventory efforts in Waterbury were directed toward quantifying these road related and woodburning emissions.

In order to better define emissions, the Village of Waterbury was broken down into a 15 by 19 grid of squares 100 meters on a side.

Up-to-date traffic counts were available from the Vermont Agency of Transportation for all the major road links in the Village. Best guess estimates were applied to the other road links.

The Waterbury woodburning survey produced detailed fuel use information for 96% of all single-family dwellings in Waterbury. Detailed information on fuel use at the Waterbury Hospital (the towns only large point source) was also available.

WOOD INVENTORY

The Waterbury emissions inventory provided very accurate and detailed information on the total amount of wood burned and the total number of houses contained within each of the grid squares. Housing density varied between 0 and 12 houses per square and total wood burned varied between 0 and 60,799 lbs. per square.

The use of wood can be reasonably well described by a second degree equation of the form: Average wood burned per dwelling unit (D.U.) = 8204.5 lb. + 37.7 D.U.^2 - 1013 D.U. (See Figure 2). It is assumed that this equation only applies to the range of densities below 12 D.U.s per grid square. At greater densities, it is assumed that the curve flattens out at about 1,000 pounds per D.U., based on an assumption that even in an urban neighborhood there will remain a fixed percentage of housing units with fireplaces, etc. Also, some sort of change is required at this point because the curve which best defines the points from 1 to 12 is parabolic in nature and begins to rise again shortly after 12 D.U.s per square.

One possible implication of the inverse relationship between dwelling density and wood use is that the maximum particulate emissions from woodburning may not occur in the most densely populated downtown areas of Vermont cities and towns but rather in the less dense "suburban" type residential neighborhoods.

Based on the Waterbury data the highest level of woodburning emissions occurs in neighborhoods with an average lot size of about .3 acres.

Wood smoke emissions based on testing done by the Agency were assumed to be 12.2 grams per kilogram of wood fuel with seasonal emissions of six (6) tons for the Village of Waterbury.

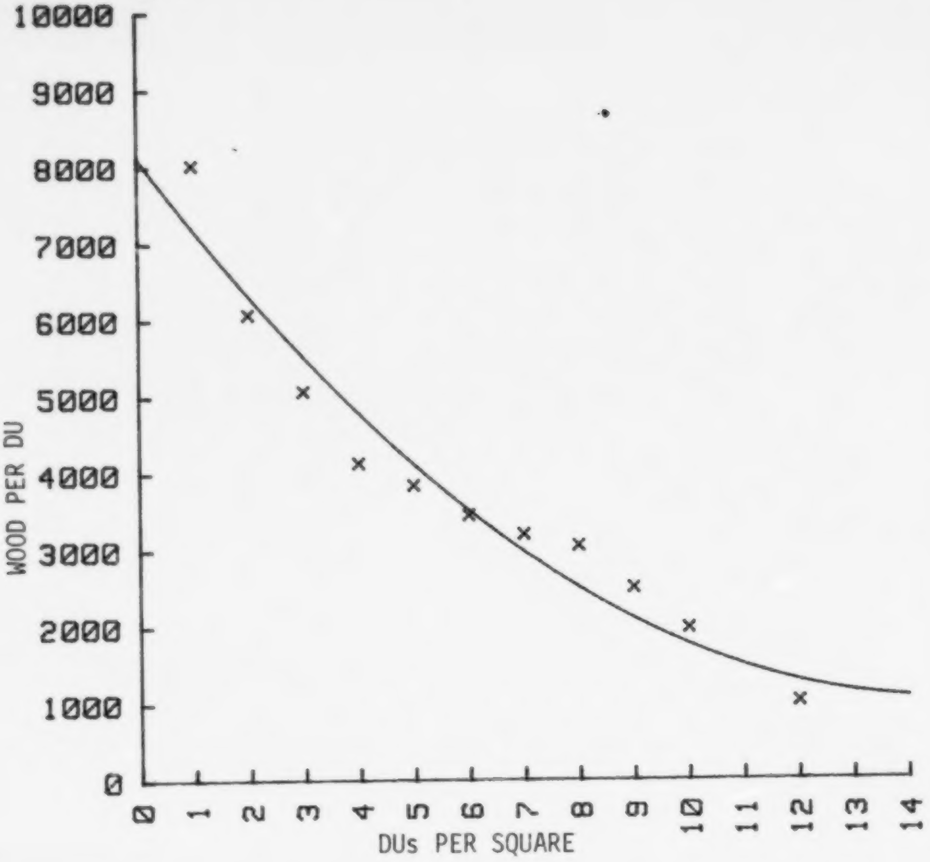


Figure 2. Wood Burned per Dwelling Unit Density

ROADWAY INVENTORY

Particulate emission rates employed were 5.448 grams per VMT for motor vehicle exhaust, tire wear and paved road reentrainment and 24 lbs. per ton of wood burned for all woodburning devices. Annual emissions in the 1.5 by 1.9 kilometer grid area were about 75 tons from road related emissions. During the winter season the road emissions would be approximately 1/4 of the annual total road emissions or 19 tons.

While the road related emissions appear to account for about 3/4 of the Village's total (25 tons) winter particulate emissions, they are more spread out throughout the grid area, particularly along the interstate. The woodburning emissions appear to be more clustered within the residential areas and might tend to have a relatively greater impact on the monitors. For example, woodburning accounts for about 2/3 of the estimated non-background emissions within the 9 grid squares centered on the Eldredge monitor.

MODELING

The use of average emission rates over an entire 24 hour period was not appropriate for modeling either wood smoke or road dust emissions as their emissions are not constant throughout the day. 24 hour average emission rates for wood smoke and road dust were refined to an hour by hour basis.

Development of hourly road related emission rates was fairly straightforward. Hourly traffic numbers from several major road links in Waterbury were averaged for each hour and then divided by the average hourly rate to produce a series of 24 factors (normalized) which could then be applied to the average emission rates. (See Table 1).

Development of hourly woodburning emission factors was more complex. First, an attempt was made to determine when, during a 24 hour period, people were loading their woodburning devices. This was done by analyzing the wood use forms which were filled out by approximately 30 woodburning-Waterbury residents during a 12 week period. These forms included information on start up time, final loading time, amount per load, number of loads per day, and in many cases, actual loading times throughout the day. Actual loading times were used whenever available, and in the other cases, the number of loads per day were distributed relatively evenly between start up time and final loading time. Some amount of discretion was used in this distribution, particularly in the lower loading range, in that loadings were not distributed evenly but rather in a manner to conform with people's work and living habits. For example: three loads per day were assumed to occur one at 7 a.m., one at 5 p.m. (return from work) and one at 10 p.m. (See Figure 3).

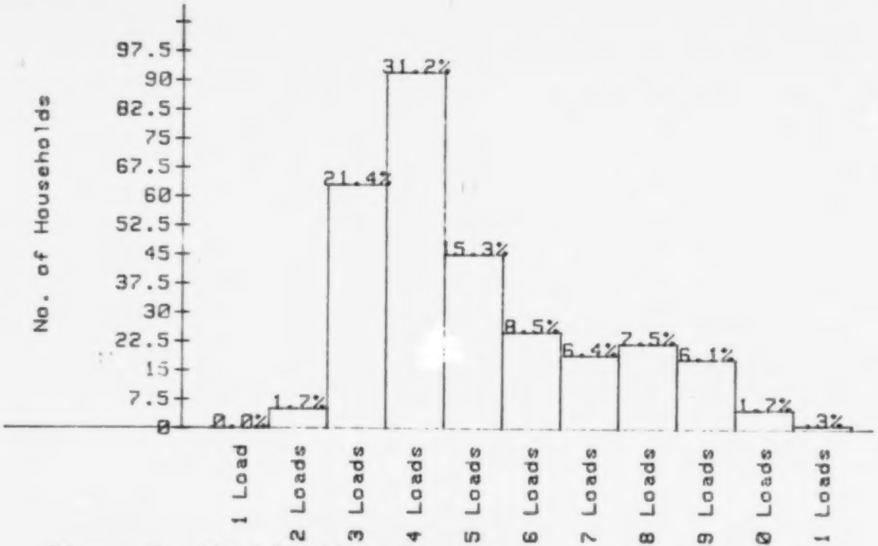


Figure 3. Wood Loadings Per Day

TABLE I. PREDICTED CONCENTRATIONS (NORMALIZED) AT APM SITE

Hour	AADT	Normalized AADT	% of Total Wood Loading	Normalized Wood Factor	APM	Normalized APM x Wind Speed	Predicted Concentrations
1	25.5	.07	0	.72	24.0	.63	.66
2	13.8	.04	0	.50	27.5	.71	.60
3	8.5	.02	0	.38	25.2	.66	.56
4	7.8	.02	0	.27	18.5	.48	.52
5	10.5	.03	.5	.23	17.2	.47	.51
6	127.8	.35	1.6	.33	21.4	.63	.61
7	397.3	1.07	15.4	1.29	39.4	1.20	1.12
8	623.7	1.69	4.7	1.28	40.1	1.35	1.26
9	412.2	1.12	4.0	1.14	29.6	1.05	1.08
10	512.2	1.39	.5	.86	26.9	1.03	1.04
11	520.8	1.41	6.7	1.09	34.1	1.43	1.13
12	570.0	1.54	6.7	1.28	33.8	1.50	1.22
13	597.8	1.62	2.4	1.09	25.6	1.13	1.17
14	524.8	1.42	1.4	.96	21.5	1.01	1.08
15	632.2	1.71	6.3	1.12	25.0	1.13	1.21
16	753.2	2.04	4.2	1.12	27.7	1.16	1.28
17	886.0	2.40	8.5	1.41	34.1	1.34	1.47
18	630.2	1.70	7.2	1.51	41.3	1.26	1.34
19	497.5	1.35	5.6	1.47	46.6	1.33	1.25
20	357.5	.97	2.0	1.20	35.7	1.01	1.06
21	279.0	.76	4.0	1.14	34.8	.97	.99
22	183.0	.50	9.6	1.50	39.2	1.09	1.06
23	189.8	.51	1.4	1.21	29.3	.80	.96
24	98.5	.27	.5	.89	23.4	.63	.79

This distribution provided an estimate of the percentage of woodburning devices being loaded during each hour of the day. This was considered important because emission tests conducted by the State of Vermont and those of Dr. Stockton Barnett of SUNY at Plattsburgh, New York[1] have indicated that emissions from any woodburning device are extremely variable and are directly dependent on stage in the burn cycle. A fresh load of wood results in a substantial drop in firebox temperature and a subsequent increase in particulate emissions. As the volatiles are driven off and the burn eventually enters its "charcoal stage", emissions are gradually reduced to a fraction of the original surge.

Based on these tests, a 10 hour burn factor curve was constructed. This curve, normalized to an average emission rate of 1 assumes that emissions will be double this average rate upon loading and will fall to half the average rate at the end of the 4 hours. Under most conditions this would probably represent a full burn cycle, but the curve was extended out to 10 hours to accommodate all night (or all day) burns in a dampened down condition. (See Figure 4).

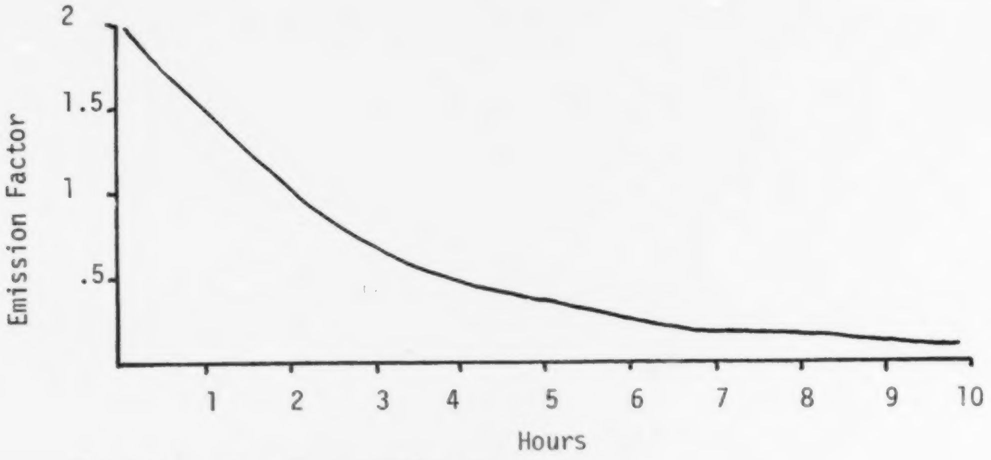


Figure 4. Wood Stove Emission Curve

Using this curve and the percentage of woodburning devices loaded during each hour of the day, emission factors were produced for each hour. Like the roadway emission factors, these woodburning factors are not emission rates but scalar factors intended to be multiplied by the average emission rates to produce a series of 24 new emission rates representative of the variation of emissions over the day.

For comparison purposes, data produced by the APM monitor was averaged over a three (3) month period to produce 24 one (1) hour average APM concentrations. At this point, it was necessary to account for the effect of dispersion on the hourly concentrations. This was done by multiplying the hourly APM concentrations by the average hourly wind speed. This is the equivalent of dividing the emissions by the wind speed - an operation performed in all dispersion equations.

These adjusted APM concentrations were then normalized to one by dividing each hourly value by the mean value. See Table 1 for summary of hourly emissions.

This resulted in the creation of three (3) new data sets (for road emissions, wood emissions, and actual particulate concentrations) emissions and concentrations themselves, but rather, of the variability of the original data sets. A multiple linear regression was then performed on these data sets with the APM as the dependent variable. The resulting regression equation was: APM = .42 + .23 Road Factor + .35 Wood Factor (r^2 = .85). A statistical T-test indicates that both the wood and the road coefficients are significant at the 99% confidence level. Because all three (3) data sets were normalized to a mean of one, the sum of the regression coefficients is also equal to 1 and the magnitude of each coefficient is representative of the relative contribution of that variable to the variance of the dependent variable. This regression equation was used to predict the concentrations shown in Figure 5. The predicted concentrations agree quite closely with the monitor values.

In this case these results might be interpreted by stating that the hourly particulate concentration at the Eldredge location is 42% background, 23% road dust, and 35% wood smoke. Of the non-background contributions, 40% is road dust and 60% is wood smoke.

This hypothesis, based on the variability of both the wood and the road factors over a 24 hour period agrees very well with the estimates of the original emissions inventory (in the 300 meter square area surrounding the Eldredge monitor, 2/3 of the total emissions are wood smoke, 1/3 is road dust). Also the annual modeling runs predicted contributions at the Eldredge location of 60% wood smoke and 40% road dust.

To further clarify and compare the impacts of wood and roadway emissions the predicted impacts are also plotted in Figure 5. Peaks in the predicted wood TSP levels are observed at approximately 7 a.m., 12 p.m., 6 p.m. and 11 p.m. These times coincide with the times that wood stoves are most commonly refueled. It can also be seen that the predicted roadway emissions peak approximately 1 hour after the wood peak in the morning, and occurs approximately one hour prior to the wood in the evening. This type of pattern could be reasonably expected.

The TSP peak which occurs around 2 a.m. (APM data) could be due to the increase in wood stove emissions that would occur in the dampened down mode, after the firebox and stove have cooled significantly causing a smouldering fire. This peak is not predicted by the regression equation since no stove refueling was expected to occur after 11 p.m.

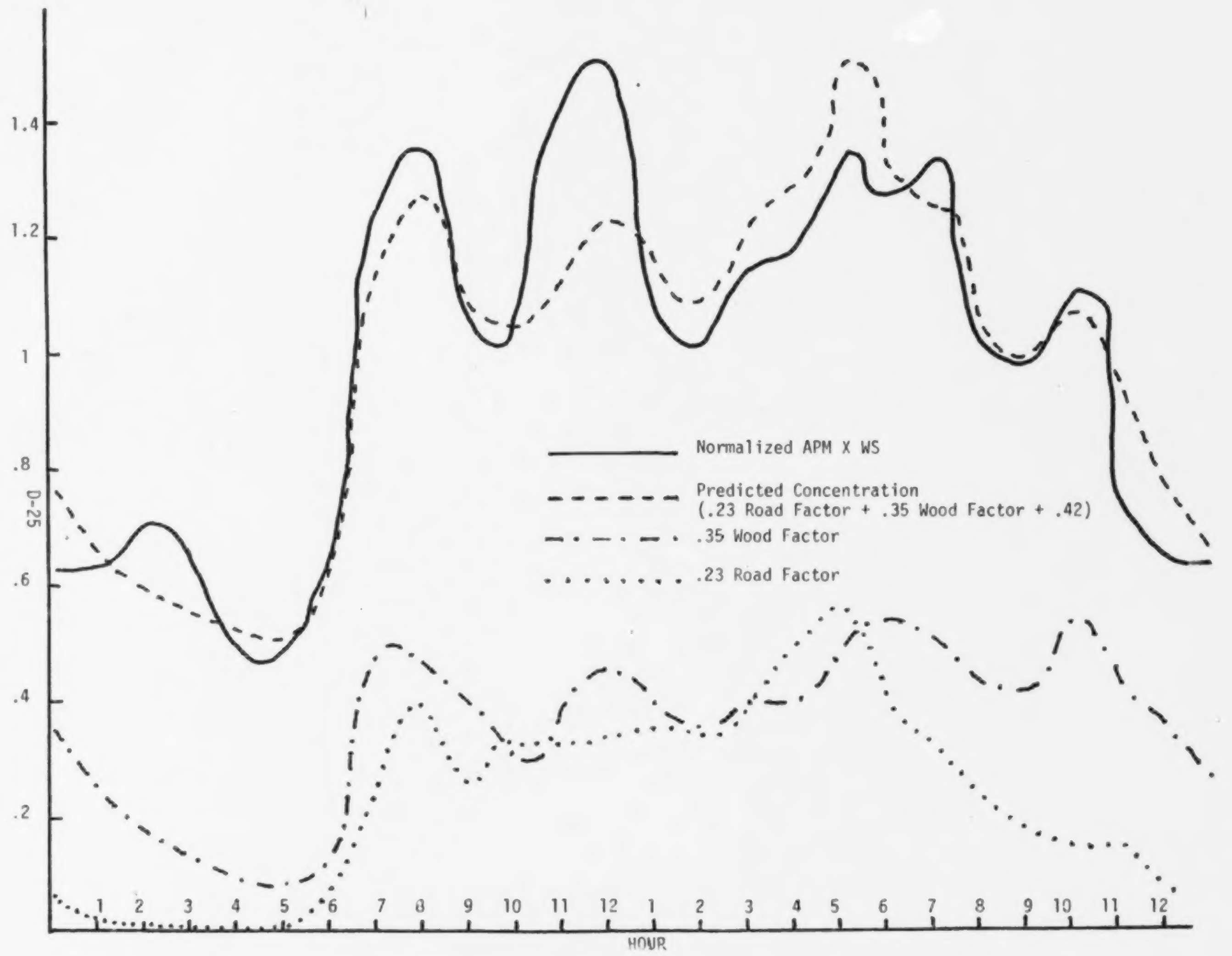


Figure 5. Measured and Predicted Average Hourly Concentrations

The Agency has not completed the analysis of the filters. This analysis should further define the impact of residential woodburning at the other sites and in Waterbury in general.

SUMMARY

In Waterbury, Vermont it has been estimated that in the residential areas wood smoke emissions could account for up to 35% of the total suspended particulates. The concentration of wood smoke will be effected by the number and density of residential woodburners and meteorological conditions.

At this time the Agency is not considering any regulatory action regarding the use of wood as a residential fuel. The present plan of action under consideration by the Agency is a public awareness/education program. The object of the program is to inform the public of the proper way to burn wood, thus hopefully reducing air pollution and at the same time minimizing creosote buildup. Additional studies on the impact of woodburning are not anticipated unless new nonattainment areas for TSP develop and wood smoke is shown to be a major contributor to the TSP levels.

REFERENCE

1. Barnett, S. G. and Shea, D., "Effects of Woodburning Stove Design on Particulate Pollution", State University of New York (1980).

POLLUTION AND FIREPLACES IN CALIFORNIA*

By: Peter H. Kosel
California Air Resources Board
1102 Q Street
Sacramento, California 95814

ABSTRACT

An examination of air pollution test results and the demography of woodburning in California indicates that although woodburning is less important than some other urban pollution sources, it may be a major contributor to pollution in some residential areas. To reduce emissions from woodburning equipment, it is better to apply design specifications to new equipment than to impose emission limits on existing equipment. The potential for marketing retrofit devices and hints for more efficient and less polluting woodburning are discussed.

INTRODUCTION

California is well known for its scenic grandeur, for its air pollution, and for tough air pollution control laws. Less famous are the peculiarities of California climate which aggravate pollution by pressing fumes and smoke down and concentrating them. Smoke rises, but in California it does not rise as far as it does in most other locations. It hits an "inversion", usually less than 1500 feet above the ground, and simply stops. Turbulent atmospheric mixing sometimes visible as towering thunderheads in the midwest is a rarity in California, as are cleansing summer rains. Pollution trapped by inversions is neither blown away nor washed from the air. When a welcome shift in weather conditions brings temporary relief from this normal year-round "autumn haze", unfamiliar and majestic mountain ranges appear as if by magic on California horizons. When the haze returns, they vanish.

It is this peculiar climate, together with increasing urbanization and industrialization, which has made California famous for smog and for regulations against the causes of smog, as well as making it the butt of a number of jokes about people who get nervous when breathing air they can not see. Agencies at the local, state, and federal levels have brought into being special cleaner cars, levied fines ranging up to six figures against industrial polluters, and issued mandates variously requiring large equipment investments and freezing industrial progress for the duration. Because of these efforts, air pollution is rarely recorded as a direct cause of death or hospitalization even in Los Angeles. Still, the easy pollution control steps have been taken and the options which remain are more difficult. While television news programs display graphic pollution indicators showing "poor", "unhealthy" or "harmful" air, planners are forced to weigh the possibility of increasing utility rates to pay for better pollution controls at power plants against the feasibility of putting the California motorist afoot or on a bus. To reduce air pollution control efforts now, however, would be to lose ground in the face of population expansion and to abandon any hope of seeing the California mountains a little more often.

---

* A paper submitted for presentation at the Wood Combustion Environmental Assessment Conference, February 24, 1981.

In this light, it will be understandable that California air pollution control workers are not easily enchanted by scenes of smoke curling up from the chimneys of a growing number of picturesque cottages and split level homes around the state.

THE BACKGROUND OF CALIFORNIA'S CONCERNS

The California Air Resources Board (ARB) is charged with assisting and overseeing local air pollution control districts around the state and coordinating statewide efforts under the scrutiny of the federal Environmental Protection Agency. In this connection, the ARB staff has tested pollution from stoves and fireplaces and has reviewed results of similar tests done by others. The pattern of fireplace and stove use in residential heating has been examined and combined with test results to estimate woodsmoke pollution in the various counties of the state.

THE CHARACTER OF WOODSMOKE

Pollution tests indicate that when a ton of wood is burned, a mixed bag of pollution weighing from 100 to 300 lbs. is produced. Most of this is toxic, colorless carbon monoxide, produced at the average rate of about 120 lbs. per ton of wood. The particulate matter which makes the smoke visible is usually produced at the rate of about 20 lbs. per ton of wood. About two thirds of this particulate matter is tarry condensed organic compounds. Tests for volatile, noncondensed organics which contribute to odors typically show about 30 lbs. of emissions per ton of wood burned. Carbon monoxide and organic pollutants are basically products of incomplete combustion. Nitrogen oxides, precursors to ozone formation and the cause of a brownish atmospheric haze, are characteristic of very hot flames and are typically produced at a moderate rate of 5 lbs. per ton of wood. Tests typically find no significant concentration of sulfur oxides in woodsmoke.

Compared to other combustion systems and fuels, residential woodburning is little different from a campfire, slightly cleaner than a home garbage incinerator, and about 8 times dirtier than oil and 25 times dirtier than natural gas when similar weights of fuel are burned. Woodburning produces proportionally more carbon monoxide and organic materials than oil or gas. Nitrogen oxides are about the same for all three fuels. Oil produces the worst emissions of sulfur oxides.

WOODSMOKE DEMOGRAPHY

Estimates based on the pattern of home heating with wood in California indicate that more wood is burned and more woodsmoke produced in semi-rural northern and mountain counties than in major metropolitan areas. Snowfall and proximity to national forests where free firewood is available seem to encourage woodburning. California's coastal population centers, San Diego, Los Angeles, and San Francisco, have mild climate, good access to natural gas utilities, and a scarcity of free firewood.

These demographic estimates are encouraging because they do not point to woodsmoke as a major cause of urban smog, but unfortunately they are not entirely definitive. They are based on census data. They reflect woodsmoke from homes where a fireplace or stove is the primary source of heat. Occasional fires built to supplement oil and gas heat or simply for enjoyment are not reflected, and it seems probable that most city dwellers use their fireplaces in this fashion. Notably, more people told census takers that they relied on wood for heat in balmy San Diego than in Los Angeles or San Francisco where nights are chillier. Firewood consumption might be better than census data as a basis for demographic studies of woodsmoke. Firewood, unfortunately, does not pass through metered pipelines as do oil and gas. The increasing popularity of woodburning further complicates the problem, introducing the factor of rapid change so that today's findings may be out of date tomorrow.

Another aspect of woodsmoke demography that merits further study is its relative contribution to air pollution in residential neighborhoods. The urban woodburner discharges pollution near ground level, right where people live. Quantitative indicators of the amount of woodsmoke in and about peoples' homes seem to be lacking but it is an inescapable fact that, on a winter's evening, the odor on the air is woodsmoke in many California neighborhoods.

THE PROBLEM OF CONTROLLING WOODSMOKE

At this time few air pollution regulations are directed at residential woodburning. Extreme cases can be treated under rarely used nuisance ordinances, but California dwellings and residential premises are frequently exempted from other regulations controlling industry and commercial operations. Experience indicates that consumer-generated pollution is best regulated by controlling manufacturers and suppliers. The long operational life of fireplaces and stoves makes this approach less feasible for woodsmoke control, however, and some program of education or regulation at the consumer level may be necessary if control is found desirable. Any woodsmoke control strategy must inevitably consider woodburning's established place as a recreational tradition and the potential of wood as a desirable supplement to fossil fuel. Some hope for a feasible woodsmoke control strategy is offered by the manifest fact that inefficiency, both in combustion and transfer of heat to the residence, is the biggest cause of woodsmoke pollution. Control of woodsmoke pollution and improvement of fuel economy in residential heating are compatible and inseparable.

THE CAUSES OF WOODSMOKE POLLUTION

Any effort to reduce pollution from woodstoves and fireplaces requires some understanding of the factors causing woodsmoke pollution. Any characteristic of operating practice, fireplace design or the fuel burned can potentially have an influence on emissions. Emissions typically vary widely from fireplace to fireplace, from fire to fire, and during the course of the same fire. Although it has been difficult to chart the influence of specific variables in many test programs, the considerable body of test data which is developing allows identification of a few factors which seem to be important to emissions.

FIREPLACE TESTS AND TESTING PROBLEMS

Fireplace and woodstove pollution has been tested by several organizations including EPA contractors, California state and local agencies, academic institutions, and by at least one car manufacturer who was seeking to put automotive emissions in perspective. Test programs have usually been intended to both estimate typical emissions and show the influence of one or more variables. No test program has yet produced data which plot on a straight line; shotgun patterns are more typical. The reason for this seems to be that changing combustion conditions vary more rapidly than they can be measured by most test methods. The use of continuous measurement instruments coupled to a computerized data acquisition system seems to be advisable in any future fireplace tests, incongruous as the juxtaposition of divergent technologies may at first appear.

Data from ARB tests on woodburning at first seemed to follow this pattern of having no clear pattern. Careful examination of ARB data, however, and comparison to tests done by Valentine, Fisher and Tomlinson of Seattle for EPA, tests by the Bay Area Air Quality Management District in San Francisco, and particularly the work of Dr. S. Butcher of Bowdoin College in Maine* led to the conclusion that certain trends, indistinct but fairly definite, are present in all test results.

Data from ARB testing is tabulated and plotted at the end of this subsection. Note cautiously that results of ARB tests for particulate matter have been found to be high in comparison to the results of tests done by others, either because ARB tests were done at about 6000 feet above sea level or due to test errors of unknown origin. The trend in ARB data, compatible with trends in tests by others, seems to be for emissions of particulate matter (especially condensed organics) and emissions of carbon monoxide and volatile organic compounds to rise when flue gas oxygen concentrations rise and when flue temperatures fall. The reasons for this and its implications are expanded upon in the discussion which follows Table 1 (Data Summary) and Figures 1 through 4 which appear on the next three pages.

---

* S. Butcher, "A Study of Wood Stove Particulate Emissions", APCD Journal July 1979, p. 724-728, and private communication.

TYPING GUIDE SHEET

TABLE 1. AIR RESOURCES BOARD FIREPLACE TESTS - SUMMARY OF RESULTS

RUN NO.	DATE	LOCATION	FIREPLACE	FUEL		STACK CONDITIONS					EMISSION FACTORS LB/TON-OF-FUEL					
				TYPE	LB/HR	TEMP. OF	FLOW DSCFM	VEL. FPS	H_2O %	EXCESS AIR %	PART.	CO	THC	NO_x	SO_2	SO_3
1	5/24/77	S. Lake Tahoe	Franklin Stove	Oak	6.57	384	120.7	12.02	2.60	1236	45.66	95.5	20.53	14.10	-	-
2	5/24/77	Same	Same	Oak	6.31	429	129.0	13.58	2.69	1290	56.06	294.5	32.98	13.42	-	-
3	5/24/77	Same	Same	Pine	4.17	498	72.6	8.32	3.69	919	90.72	102.1	9.26	6.50	-	-
4..	5/24/77	Same	Same	Pine	4.53	354	103.9	10.11	3.62	1365	78.23	106.1	18.38	5.40	-	-
5	5/25/77	Tahoe Vista	Fisher Stove	Oak	8.69	608	52.8	12.57	8.21	306	15.16	72.4	5.99	-	-	-
6	5/25/77	Same	Same	Oak	7.00	502	38.9	9.43	11.27	638	25.72	20.4	0.49	-	-	-
7	8/2/77	Kingvale	Same	Pine	10.53	632	34.3	8.37	10.24	129	29.03	79.3	-	3.20	0.00	0.10
8	8/2/77	Same	Same	Pine	2.70	645	36.7	8.90	8.56	928	53.35	65.0	-	8.64	0.00	0.45
9	8/3/77	Same	Same	Coal	5.86	586	30.3	7.66	16.78	150	21.00	8.7	-	10.41	24.89	0.30
10	8/3/77	Same	Same	Coal	5.25	606	35.2	8.79	14.14	276	29.08	51.0	-	14.54	29.88	0.89
11	6/14/77	Homewood	Brick Fireplace Glass Doors Shut	Oak	46.71	524	508.6	23.52	4.79	830	34.46	155.1	73.06	4.61	-	-
12	6/14/77	Same	Same	Oak	26.57	432	420.6	17.78	5.60	1171	46.13	240.9	96.94	3.36	-	-
13	6/14/77	Same	Brick Fireplace Glass Doors Open	Oak	32.22	300	669.7	23.82	4.55	1306	57.00	189.5	37.31	3.14	-	-
14	6/14/77	Same	Same	Oak	31.73	294	712.4	24.78	2.99	1633	126.99	124.4	15.27	2.06	-	-

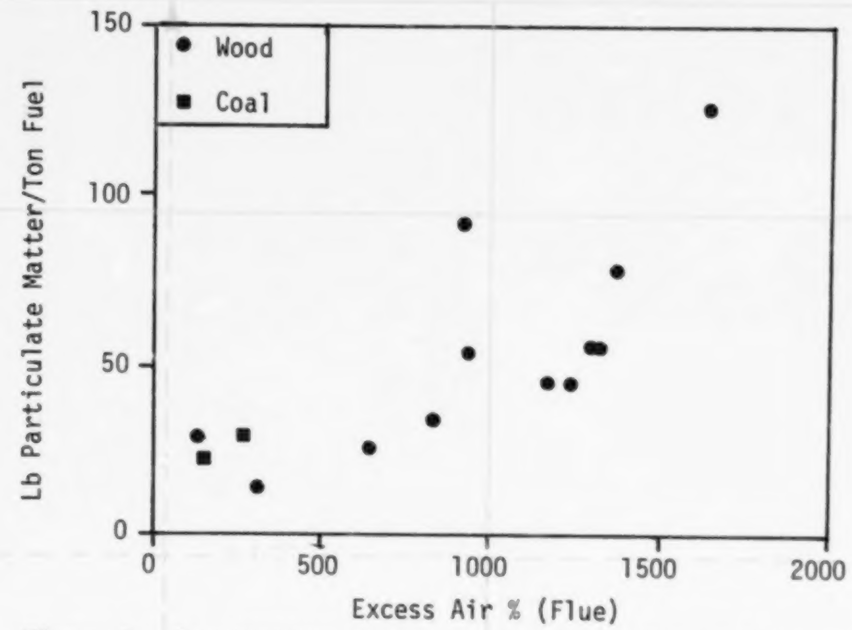


Figure 1. Particulate Matter Emissions vs. Excess Air

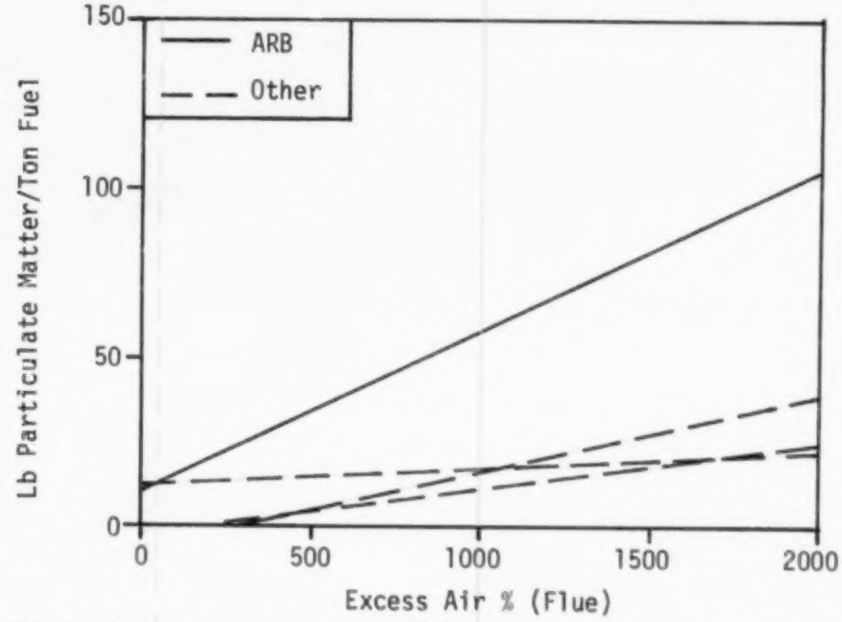


Figure 2. Trends of Particulate Matter Emissions vs. Excess Air in Tests by ARB and by The Bay Area Quality Management District (San Francisco), Valentine, Fisher & Tomlinson (Seattle), and Bowdoin College (Brunswick, Maine).

TYPING GUIDE SHEET

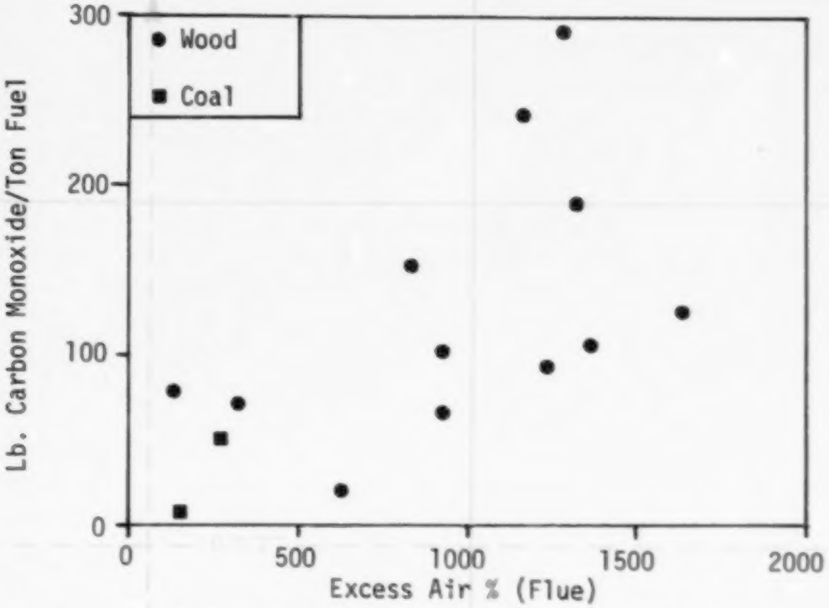


Figure 3. Carbon Monoxide Emissions vs. Excess Air

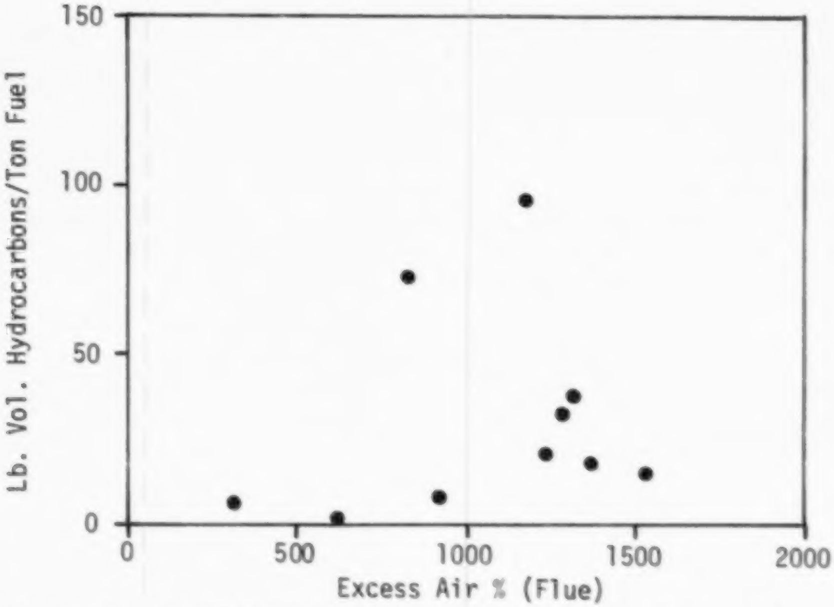


Figure 4. Volatile Hydrocarbon Emissions vs. Excess Air. Hydrocarbons are expressed as methane.

TYPING GUIDE SHEET

FUEL FACTORS

Fuel type seems to have less influence on pollution emissions than do combustion system design and operating practice. Repeatedly, comparisons of hardwoods and softwoods have shown little, if any, difference in emissions. Some ARB data indicate that the ash content of the fuel may affect emissions of filterable particulate matter. Condensible organic material (which usally passes through filters) seems largely unaffected by wood species. Some wood species may burn differently in the green state but be very similar once they are dried or seasoned. Drying and other fuel preparation activities are reasonably considered as aspects of operating practice and will be mentioned below in that context.

COMBUSTION SYSTEM DESIGN FEATURES

Combustion system design seems to be more important to emissions than fuel type. Different stoves and fireplaces usually produce different emissions. The influence of even major design features, however, has been difficult to isolate in testing. This is due to the many design features such as grate, flue, draft control, damper, firebox insulation, and baffle arrangements which may affect emissions, and to inevitable variations in operating practice during testing. Generally, lower pollutant emissions are associated with higher flue gas temperatures. These, in turn, seem to prevail only when some form of draft control prevents the influx of large amounts of dilution air unnecessary to the combustion process. Higher fuel efficiency in residential heating generally accompanies the high flue temperatures and low dilution air rates associated with clean burning. Effective delivery of air to the combustion zone may play a crucial role, since a forced draft system with a fan has reportedly proved to eliminate most visible smoke.

THE IMPORTANCE OF OPERATING PRACTICE

Operating practice in residential woodburning includes fuel preparation, regulation of the combustion rate by fuel addition and poking, and adjustment of dampers. Tests indicate that the high flue gas temperatures associated with efficiency and clean burning are also associated with high combustion rates. A tendency of intake air flow to remain relatively constant as combustion rates vary can be predicted by theoretical reasoning. Homeowners are thus best advised to build large fires within the limits of safety and to split wood and allow it to dry so that it will burn briskly rather than smolder. Severe draft restrictions which reduce the combustion rate are inadvisable both from fuel efficiency and pollution control standpoints. Smoke from home heating may be reduced by 50 percent or more by following this "large fire" rule. When a fire is built simply for enjoyment in an open-front fireplace, however, it may be possible to reduce smoke even more by simply keeping the fire small and burning less wood.

BASIC COMBUSTION PROCESS CONSIDERATIONS

The very nature of the pollutants in woodsmoke gives valuable perspective on the factors important in their formation. Carbon monoxide and organic compounds predominate. These are obviously products of partial combustion which pass from the firebox as gas or vapor. They would be eliminated if combustion were complete. Generally, near complete combustion will be accomplished if air and fuel are well mixed and held at temperatures of 1200° to 1500°F for a second or so. Since no deficiency of oxygen is shown in test results, inadequate mixing and low combustion chamber temperatures are prime suspects in the search for the cause of woodsmoke.

WAYS AND MEANS FOR WOODSMOKE POLLUTION CONTROL

Requiring homeowners to install pollution control equipment on existing fireplaces and stoves does not seem feasible economically. The expense to individuals would be significant. Enforcement would be difficult. Justifiable citizen outrage could be expected if woodburning as a private recreational tradition were thus attacked. In new installations intended for residential heating, however, these considerations do not apply. There is a considerable market for retrofit equipment such as fireplace inserts and special grates to improve fuel efficiency. Efficiency is a major selling point in new equipment. Because clean burning is essential for good efficiency, well designed equipment to reduce pollutant emissions seems inherently marketable. Equipment to reduce woodsmoke emissions can be attractive regardless of its effect on efficiency, since excessive smoke can be an irritant to the woodburning homeowner and offend neighbors.

FORCED DRAFT

Numerous avenues are available to those interested in designing equipment for pollution control and efficiency improvement. Forced draft fans, for instance, are rarely found on residential woodburning equipment but are common elsewhere. Forced draft offers the potential for improved fuel air mixing and better combustion in the available firebox volume due to improved turbulence. A 5 watt toy motor could move as much combustion air as the buoyancy of hot flue gases does in a typical fire. Forced draft need not be electrical. The ample thermal energy available in wood burning makes it reasonable to consider simple heat engines, possibly with temperature actuated valves, for augmenting combustion turbulence. In retrofit applications, forced draft systems should allow for higher combustion temperatures if necessary by including or incorporating special grates or refractory linings.

INSTRUMENTATION AND COMBUSTION CONTROLS

Another approach to pollution control would be to provide instrumentation and controls which allow a woodburning appliance to be operated more efficiently. Temperatures and pressures can generally be measured more economically than other combustion parameters. Firebox and flue temperatures are reasonable indicators of combustion efficiency. The pressure drop across inlet air dampers is related to the energy available for fuel/air mixing. With even the simplest instrumentation, cleaner burning is achievable in manual operation. Automatic actuation of inlet air dampers or other controls could allow continuous clean burning over a wider range of combustion rates. The small forces necessary and the proven reliability of such equipment as pilot light shutoffs indicate that automatic damper controls for wood burning should be quite feasible.

IMPROVED AIR INTAKES

In connection with designs intended to augment inlet air velocity or regulate its volume, provisions to direct it effectively should be developed if possible. No clear indication of the effect of inlet damper configuration is apparent in pollution test results. Reason indicates, however, that dampers and air passages should direct air toward the fuel load and combustion zone and avoid unnecessary friction which would reduce air velocity. Preheating air by drawing it past hot surfaces might have some potential for increasing combustion temperatures, but would entail added air friction.

BETTER USE OF CERAMICS AND GLASS

A large range of applications for refractories, ceramics, and glass seems to exist in woodburning. The need for higher combustion temperatures leads to a need for insulation and refractories to separate combustion gases from metal firebox walls. Lightweight materials or ceramic structures which rapidly come up to temperature when a fire is started seem desirable. It may be possible to design "insert structures" which can both insulate the combustion zone and direct clean exhaust toward heat transfer surfaces. Some work has even been done on ceramic catalysts for use in woodburning systems. Last but not forgotten, glass doors and peek holes find a use in woodburning by simply allowing the homeowner to see whether the fire is burning well or only smoldering.

SUMMARY

Woodburning in fireplaces and stoves is a traditional source of heat, cheer and smoke. Smoke, however traditional, is unfortunately synonymous with air pollution. The emissions of carbon monoxide, particulate matter and hydrocarbons from typical residential woodburning are many times those which would result from burning oil or gas. Woodsmoke pollutants are basically products of inefficient combustion. The type of wood burned seems to have less effect on emissions than do combustion system design and operating practice. Poor fuel/air mixing and low combustion chamber temperatures are prime suspects in the search for causes of woodsmoke. A variety of means to reduce pollution and improve fuel efficiency are potentially feasible. These include provision of forced draft, improving air intakes in natural draft, addition of instrumentation and automatic combustion controls, better use of ceramics and glass, and even catalysts. Because efficiency is a major selling point for new woodburning equipment and retrofit accessories, and because woodsmoke reduction is inseparable from improved fuel economy, it seems likely that well designed equipment to reduce woodsmoke can be profitably marketed. Manufacturers are well advised to keep abreast of pollution control developments so as to remain competitive and to ensure that they have a place in tomorrows marketplace.